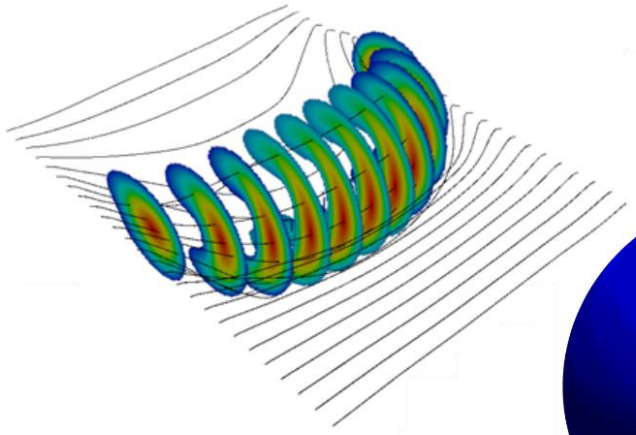

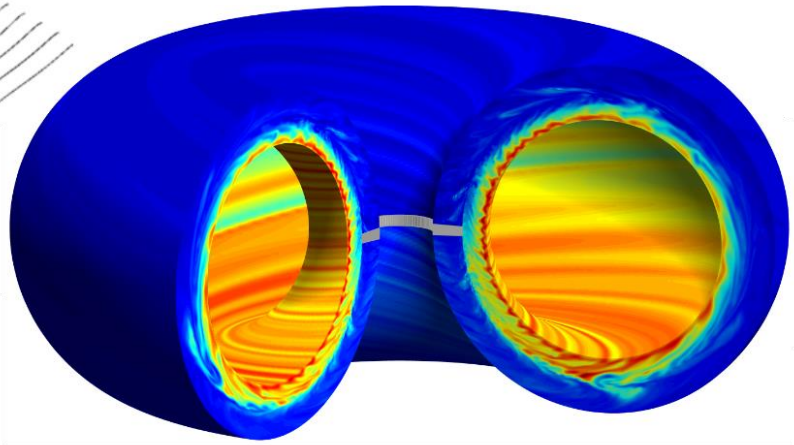

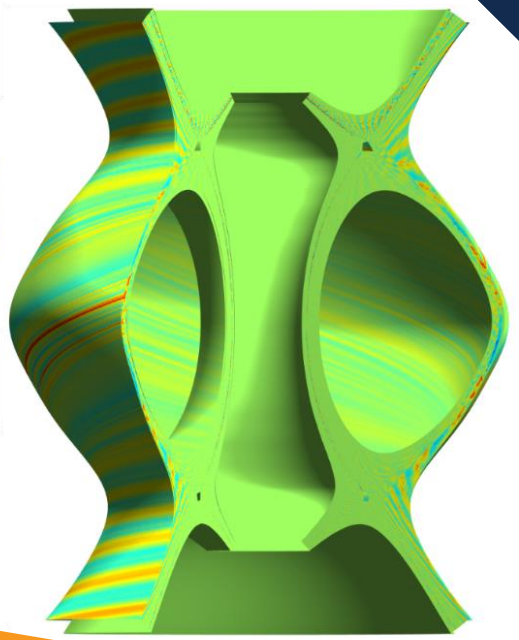

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Progress in simulating scrape-off layer plasma dynamics with STORM

F. Riva, D. Hoare, F. Militello, S. Newton, T. Nicholas, J.T. Omotani, D. Schwörer, N.R. Walkden, and B.D. Dudson

This work was funded by the RCUK Energy Programme
[Grant number EP/P012450/1]

Energy

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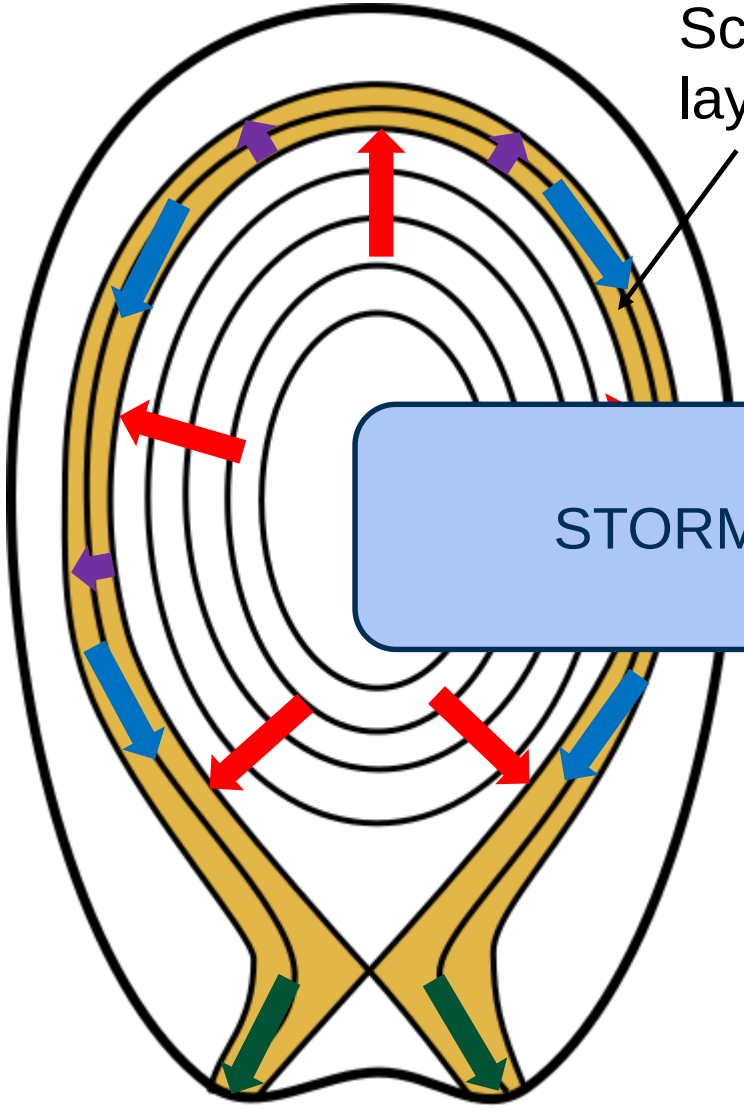
CULHAM CENTRE FOR FUSION ENERGY

The scrape-off layer (SOL) region



Roles of the SOL

- Heat exhaust

Plasma outflowing from the core

rticle loads
removal

STORM module of BOUT++

➔Need to understand transport mechanisms in the SOL

- Impurity control

Parallel flows

Sheath losses

- Filaments (generation, motion,…)
- Turbulence dynamics

STORM: the workhorse of our projects

https://github.com/boutproject/STORM

Past

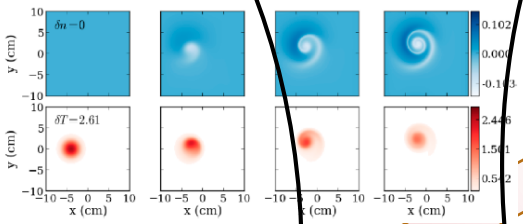
Past

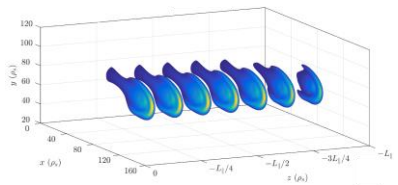
Present

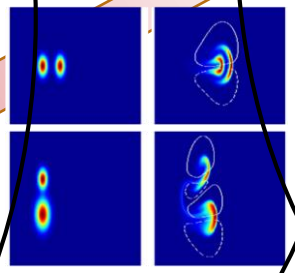
Future

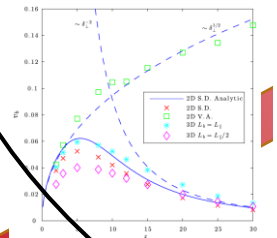
- The STORM isothermal model
- Verification and validation
- Comparison with 2D simulations
- Effects of filaments' amplitude

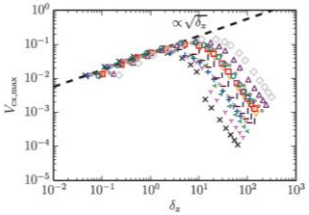
- The STORM thermal model
- Validation

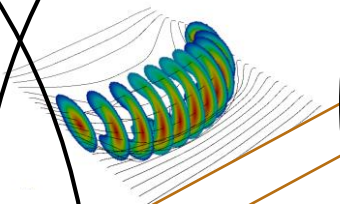


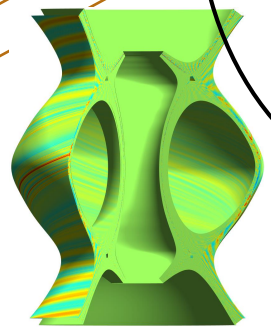




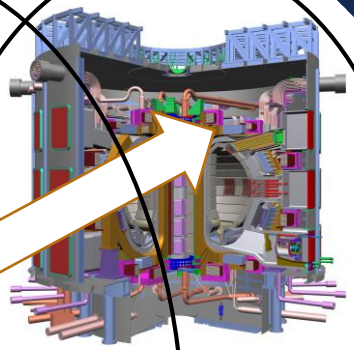








- Plasma turbulence



- What's next?

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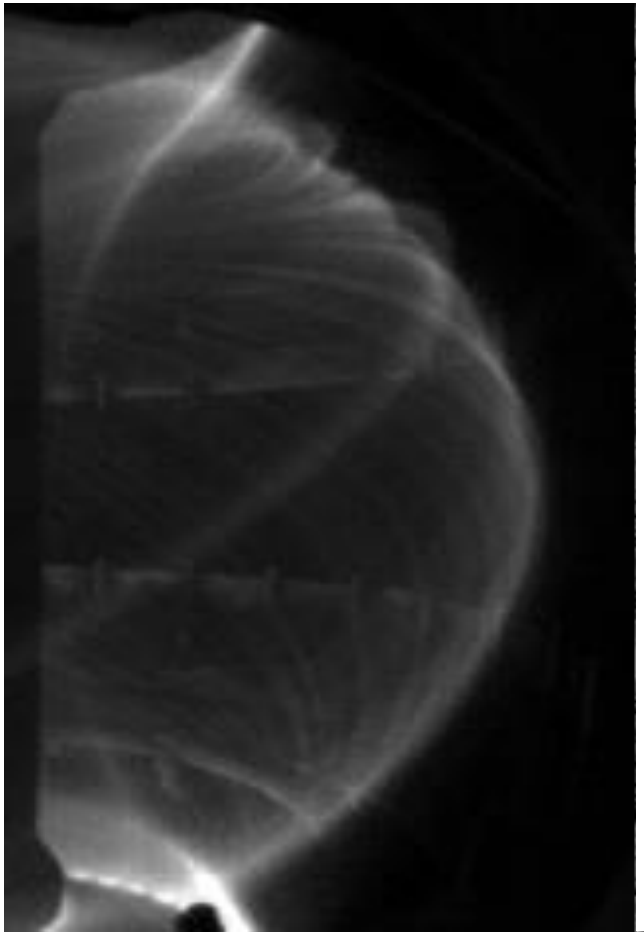
Plasma properties in the SOL



- Large fluctuations
- Fairly cold $T \lesssim 100\,\mathrm{eV}$
- Losses at the sheath
- Low frequencies $\omega \ll \Omega_{ci}$

[Walkden *et al.*, NME (2017)]

A plasma model for the SOL

UK Atomic Energy Authority

- High collisionality $\nu^* \gg 1$ ⟶ Braginskii equations
- Slow timescales, $\rho_s \ll L_\perp$ ⟶ Drift reduction

$$\mathbf{v}_i \approx U\mathbf{b} + \mathbf{v}_{E\times B} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d}{dt}\mathbf{v}_{E\times B}$$

- Slab geometry ⟶ Magnetic curvature and gradients added artificially
- Isothermal electrons ⟶ $T = 1$
- Boussinesq approximation ⟶ $\nabla \cdot \left(n \frac{d\nabla_\perp \phi}{dt} \right) \approx n \frac{d\nabla_\perp^2 \phi}{dt}$
- Electrostatic ⟶ $\mathbf{E} = -\nabla\phi$

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A plasma model for the SOL

- Continuity equation

$$\frac{\partial n}{\partial t} = \underbrace{-\mathbf{v}_{E\times B}\cdot\nabla n}_{E\times B\ \text{advection}} - \overbrace{\nabla_{\parallel}(nV)}^{\text{Parallel advection and compression}} + \underbrace{g\left(\frac{\partial n}{\partial z} - n\overbrace{\frac{\partial \phi}{\partial z}}^{E\times B\ \text{compression}}\right)}_{\text{Diamagnetic advection and compression}} + \underbrace{\nabla\cdot(\mu_n\nabla n)}_{\text{Classical and neoclassical diffusion}} + \overbrace{S_n}^{\text{Plasma sources}}$$

- $\nabla\cdot\mathbf{J} = 0$

$$\frac{\partial \Omega}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla\Omega - U\partial_{\parallel}\Omega + \frac{1}{n}\nabla_{\parallel}\left[n(U-V)\right] + \frac{g}{n}\frac{\partial n}{\partial z} + \nabla\cdot(\mu_{\Omega}\nabla\Omega)$$

- Ohm's law

$$\frac{\partial V}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla V - V\partial_{\parallel}V + \frac{m_i}{m_e}\left[\partial_{\parallel}\phi + \nu_{\parallel}(U-V) - \frac{1}{n}\partial_{\parallel}n\right] - V\frac{S_n}{n}$$

- Parallel ion momentum equation

$$\frac{\partial U}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla U - U\partial_{\parallel}U - \partial_{\parallel}\phi - \nu_{\parallel}(U-V) - U\frac{S_n}{n}$$

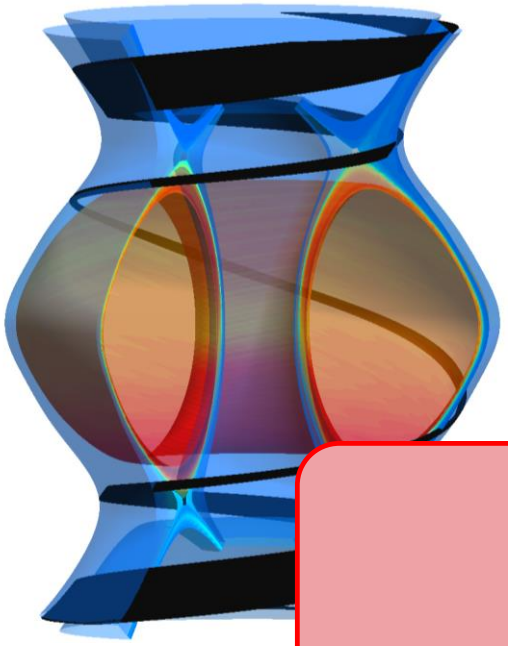
- Poisson's equation

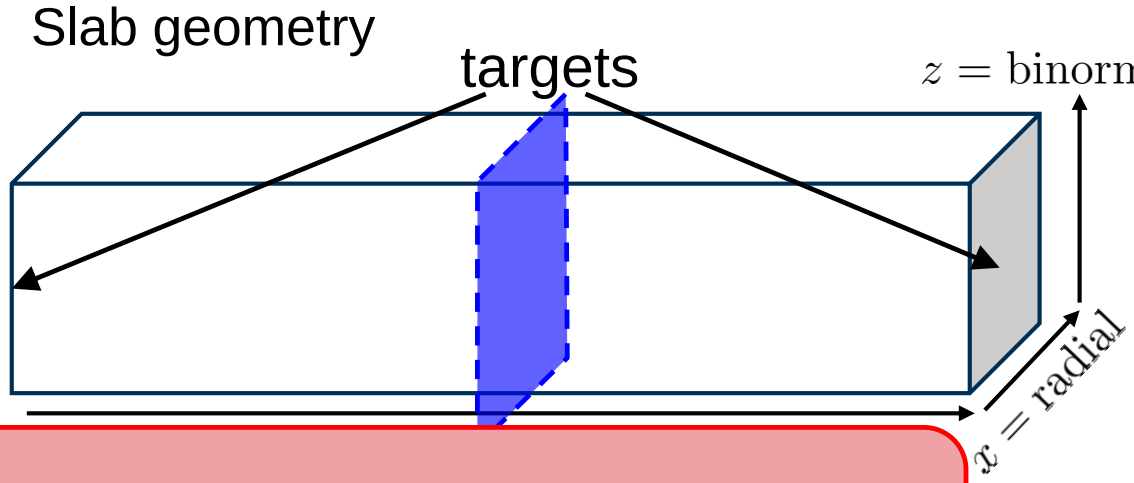
$$\Omega = \nabla_{\perp}^2\phi$$

- Bohm-Chodura boundary conditions

$$U|_{\text{target}} \gtrless \pm 1,\ V|_{\text{target}} = \pm\exp(\phi_{\text{wall}} - \phi)$$

The STORM module of BOUT++





Is the code bug free?

- Implemented within BOUT++, solved with pvode/cvode
- Arakawa scheme for $E \times B$ terms
- U and V staggered in y
- Upwind schemes for parallel advection terms
- Central finite difference schemes for other terms

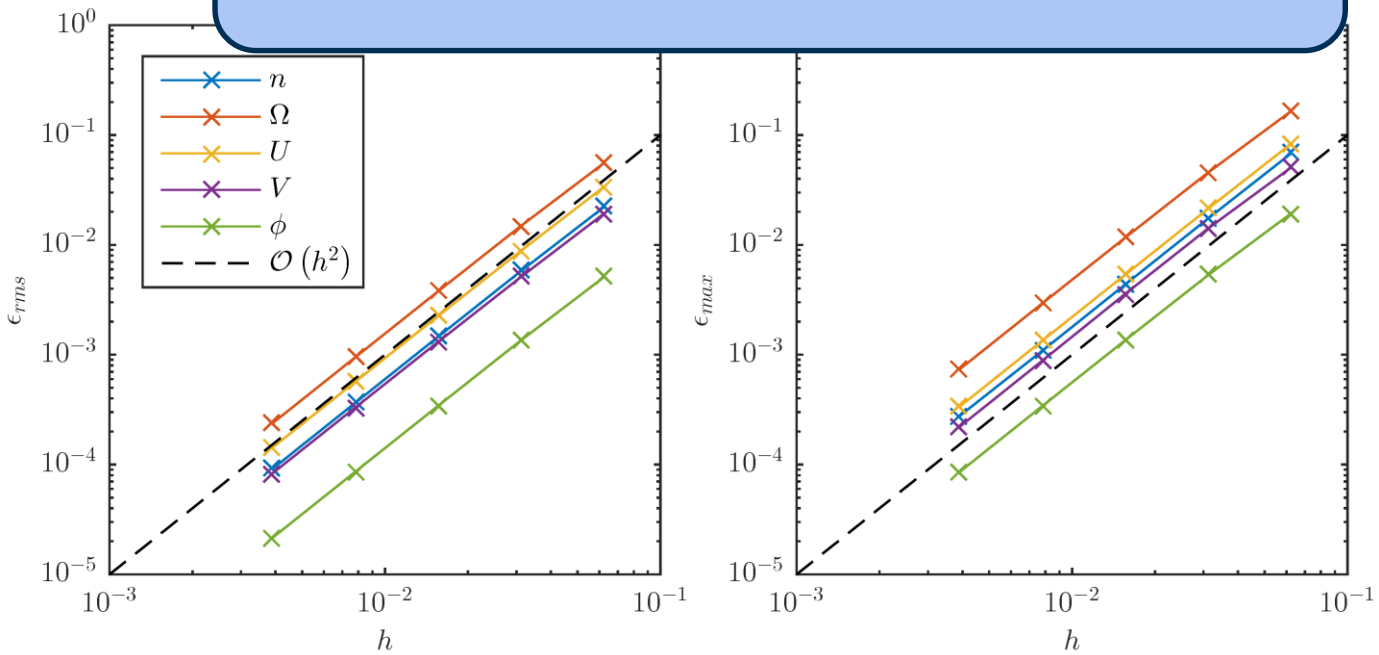
Code verification, order-of-accuracy test

Method of manufactured solutions
[Roache *et al.*, AIAA J. (1984)]

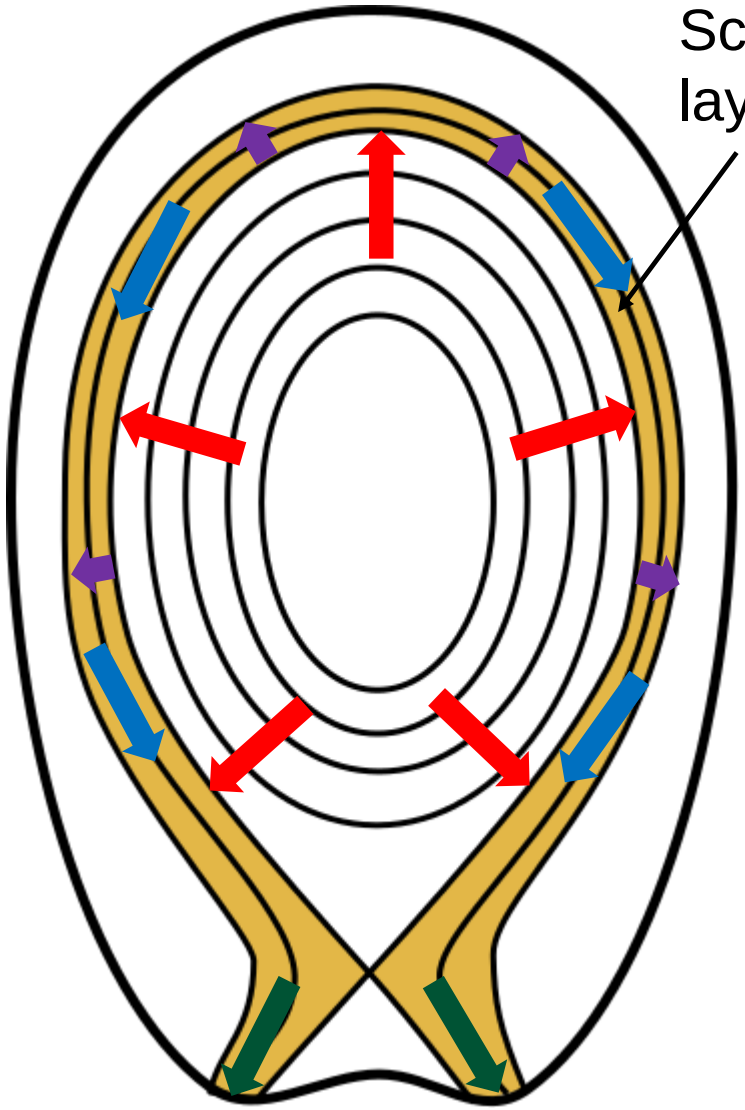
1) Choose arbitrary function g
2) Define $S = M(g)$
3) Solve $M_h(g_h) - S = 0$
4) Compute

(see also BO

STORM is verified!



The scrape-off layer (SOL) region



Roles of the SOL

- Heat exhaust

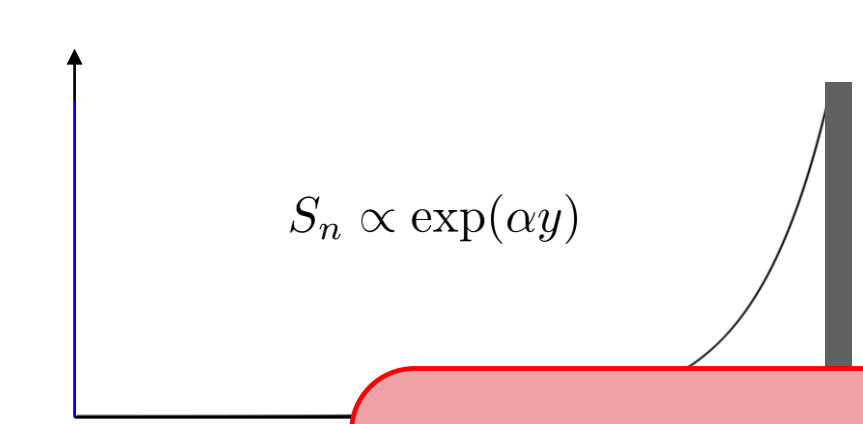
What are the heat and particle loads on vessel components?

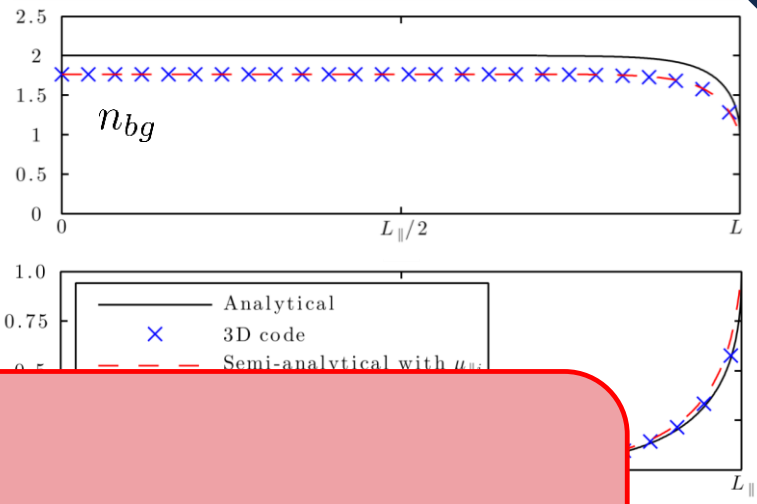
How to reduce them?

➔Need to understand <u>transport</u> mechanisms in the SOL

- Filaments (generation, motion,…)
- Turbulence dynamics

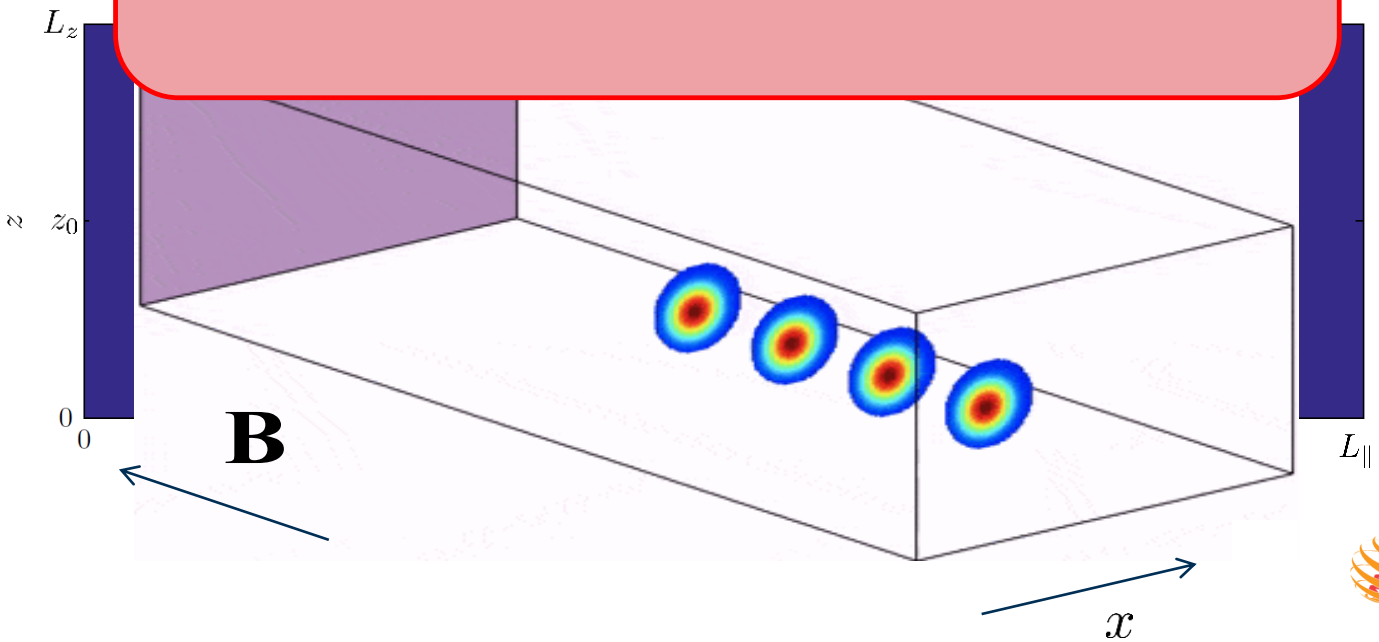
Plasma background & seeded filaments





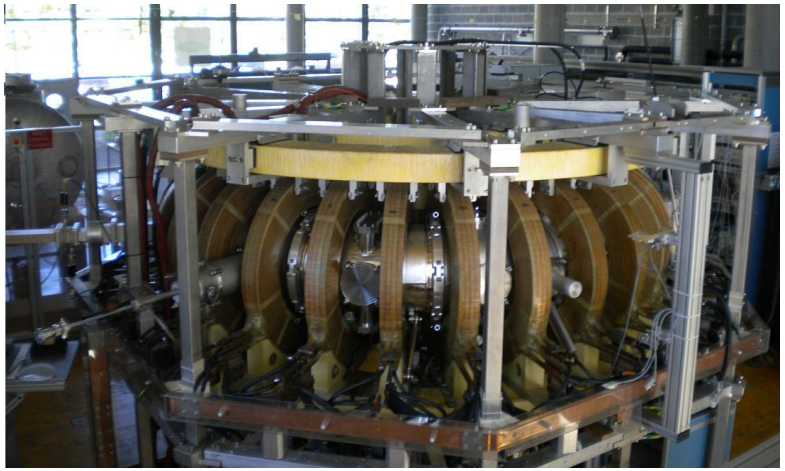
et al., PoP (2014)]

Are we capturing
the filament dynamics correctly?

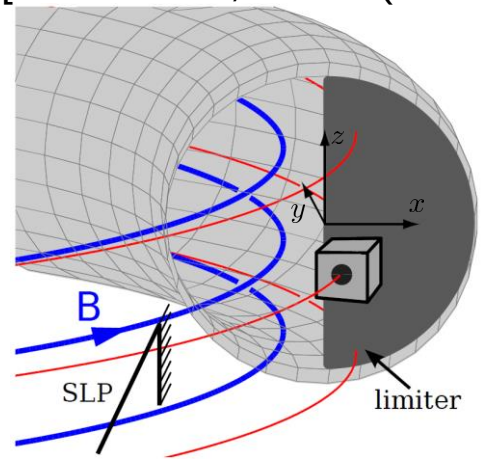


Validation against TORPEX experiment

TORPEX [Fasoli *et al.*, PoP (2006)]

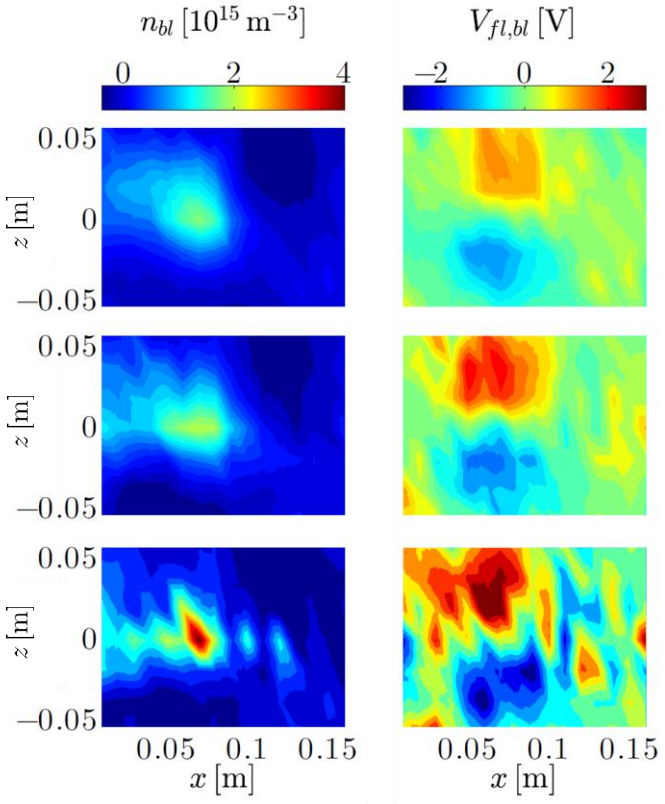


[Furno *et al.*, PPCF (2011)]



Provide

- Initial condition for simulations (density, …)
- Observables (radial velocity, …)



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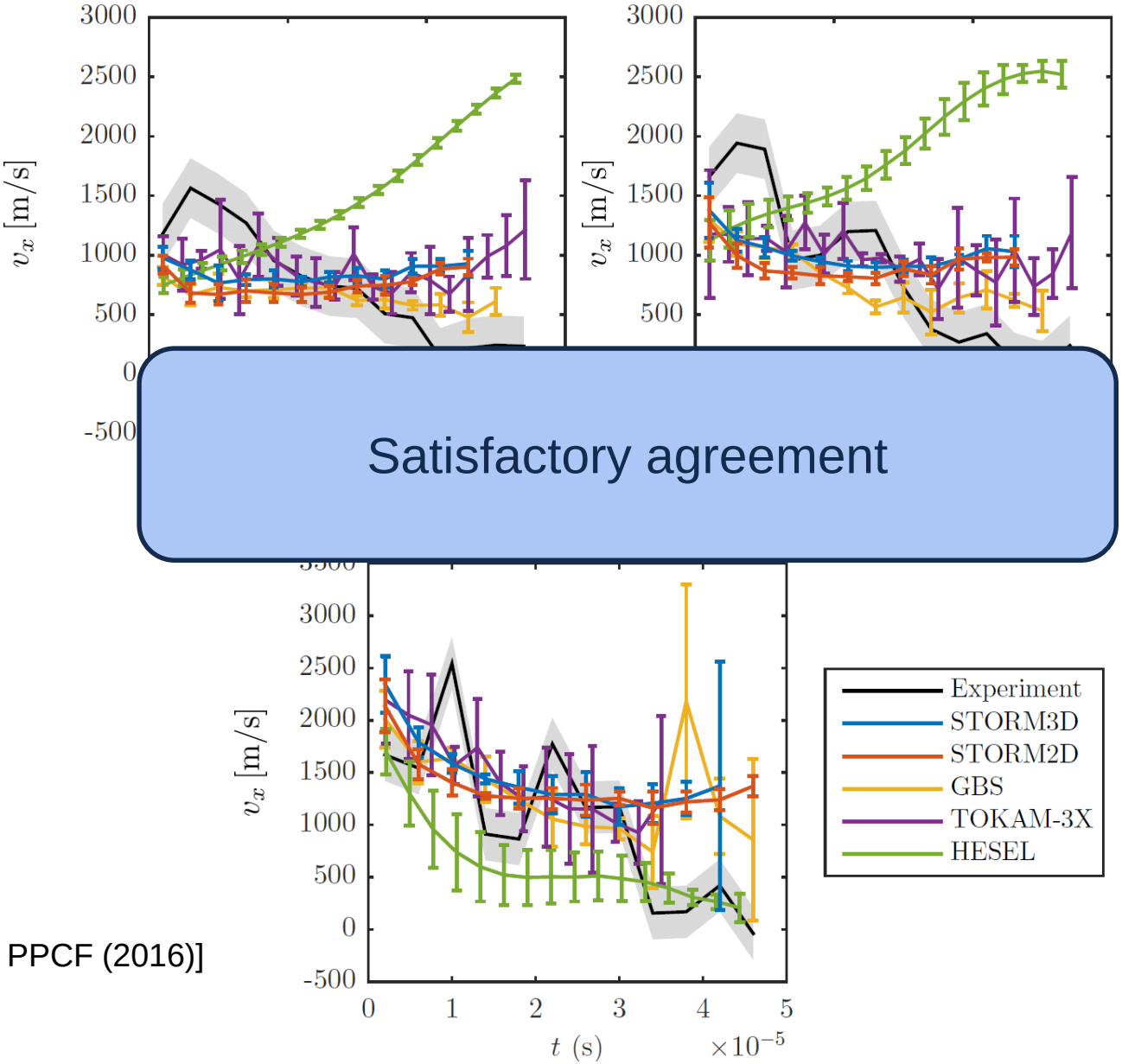

Satisfactory agreement

[Riva *et al.*, PPCF (2016)]

2D closures

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Used in the past to investigate plasma turbulence and filament dynamics

[Krasheninnikov et al., JPP(2008)]

How do they compare to 3D models?

Shea

$$k_{\parallel} = 0$$

$$(nU)|_{\text{target}} = \pm n|_{\text{midplane}}$$

$$(nV)|_{\text{target}} = \pm n \exp(\phi_{\text{wall}} - \phi)|_{\text{midplane}}$$

closure

$$U\nabla_{\parallel} = V\nabla_{\parallel} = \frac{1}{L_{\parallel}}$$

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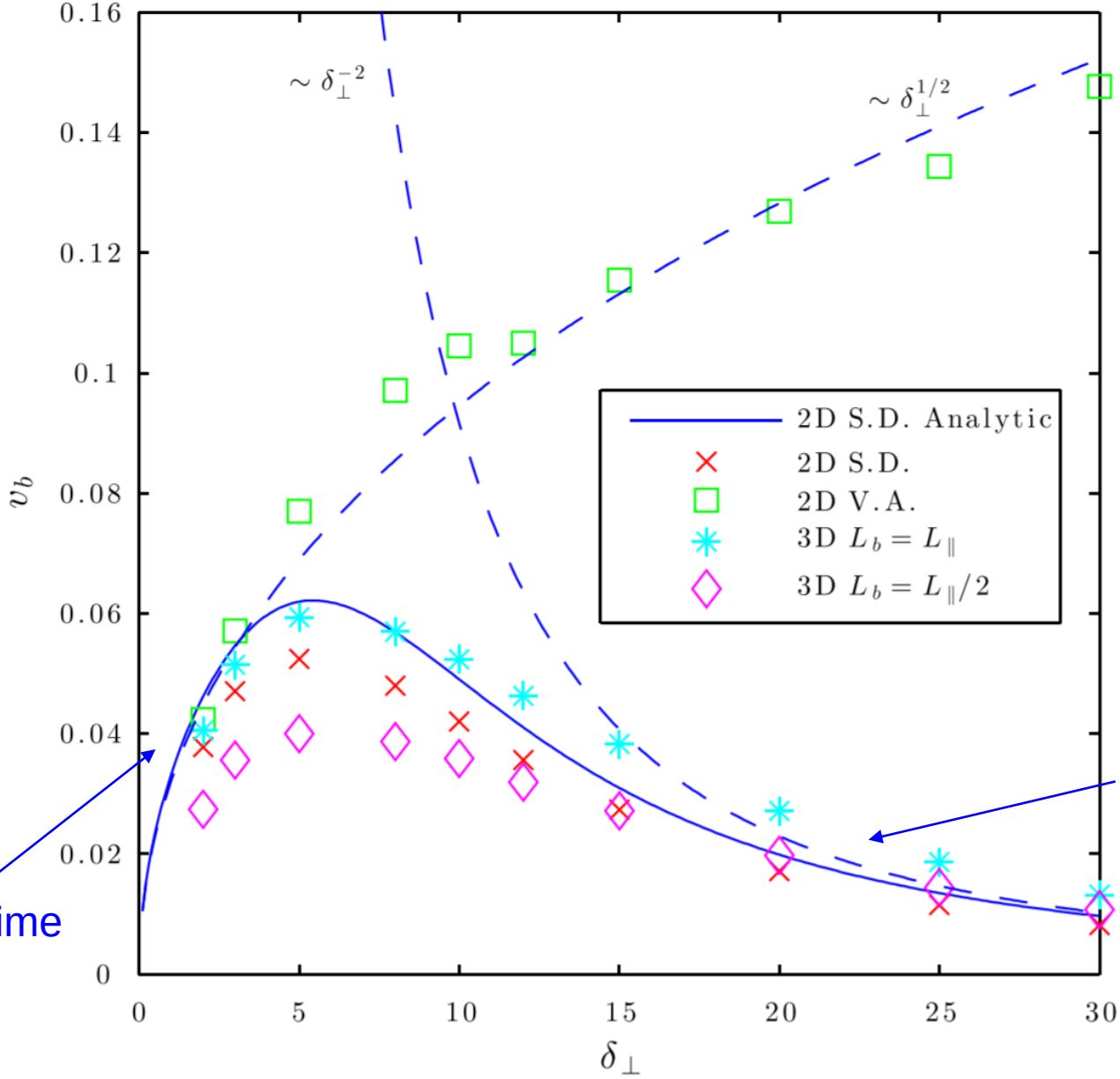
2D-3D comparison

[Easy *et al.*, PoP (2014)]



Inertial regime

Sheath current regime

Effects of filaments' amplitude

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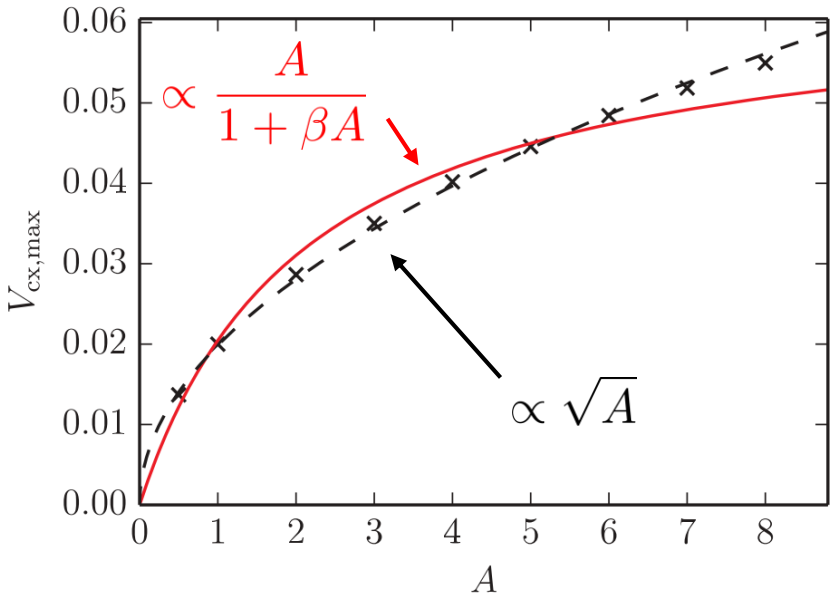
Implemented multigrid within BOUT++ ⟶ Relaxed Boussinesq approximation

(project coordinated by J.T. Omotani)

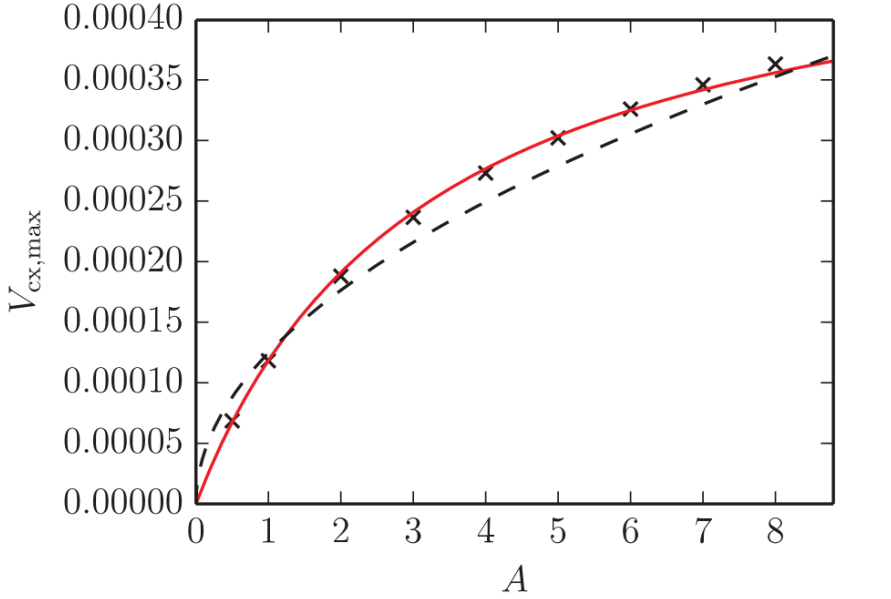
$$\Omega = \nabla \cdot (n \nabla_\perp \phi)$$

$$\frac{\partial \Omega}{\partial t} = -\mathbf{v}_{E\times B} \cdot \nabla \Omega - U \partial_\parallel \Omega + \nabla_\parallel \left[n(U - V) \right] + g \frac{\partial n}{\partial z} + \nabla \cdot (\mu_\Omega \nabla \Omega) - \frac{1}{2} [v^2_{E\times B}, n]$$

Inertial regime $\propto \sqrt{A}$



Sheath current regime $\propto \frac{A}{1+\beta A}$



[Omotani *et al.*, PPCF (2015)]

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A plasma model for the SOL

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- High collisionality $\nu^* \gg 1$ ⟶ Braginskii equations
- Slow timescales, $\rho_s \ll L_\perp$ ⟶ Drift reduction

$$\mathbf{v}_i = U\mathbf{b} + \mathbf{v}_{E\times B} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d}{dt}\mathbf{v}_{E\times B}$$

- Slab geometry ⟶ Magnetic curvature and gradients added artificially
- Isothermal electrons ⟶ $T = 1$
- ~~Boussinesq approximation~~
- Electrostatic ⟶ $\mathbf{E} = -\nabla\phi$

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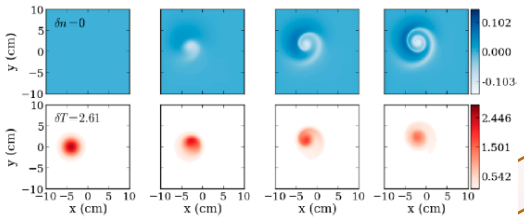
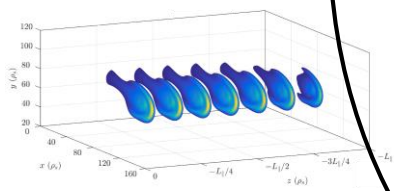
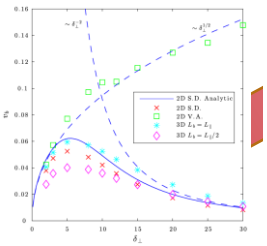
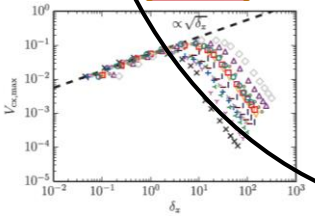
- The STORM isothermal model
- Verification and validation
- Comparison with 2D simulations
- Effects of filaments' amplitude

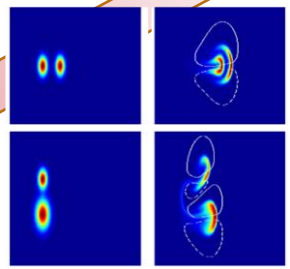
- The STORM thermal model
- Validation

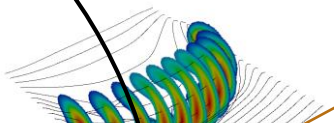


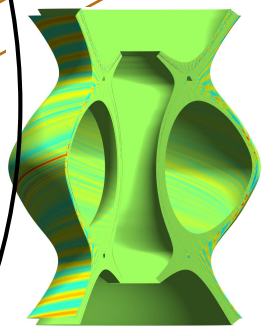




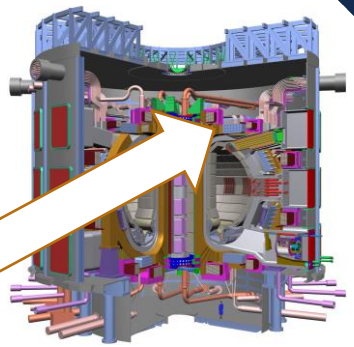








- Plasma turbulence



- What's next?

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Thermal electrons

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Filaments may carry significant temperature perturbations

- Extension of isothermal model $g\frac{\partial n}{\partial z} \rightarrow g\frac{\partial (nT)}{\partial z}, \ ...$
- Energy equation $\frac{3}{2}n\frac{\partial T}{\partial t} = -\nabla_{\|} q_{\|} + ...$
- Boundary condition for heat flux

$$Q_{\|}|_{\text{target}} = \gamma (nT^{3/2})|_{\text{target}} \qquad \gamma \approx 2 - 0.5 \ln \left(2\pi \frac{m_e}{m_i} \right)$$

$$q_{\|} = Q_{\|} - \frac{5}{2} nTV - \frac{1}{2} m_e n V^3$$

More details in [Walkden *et al.*, PPCF (2016)]

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A plasma model for the SOL

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- High collisionality $\nu^* \gg 1 \longrightarrow$ Braginskii equations
- Slow timescales, $\rho_s \ll L_\perp \longrightarrow$ Drift reduction

$$\mathbf{v}_{E\times B}$$

- Slab geom… …dients added
- ~~Isotherma~~
- ~~Boussinesq approximation~~
- Electrostatic $\longrightarrow \mathbf{E} = -\nabla\phi$

Did we improve our modeling capabilities?

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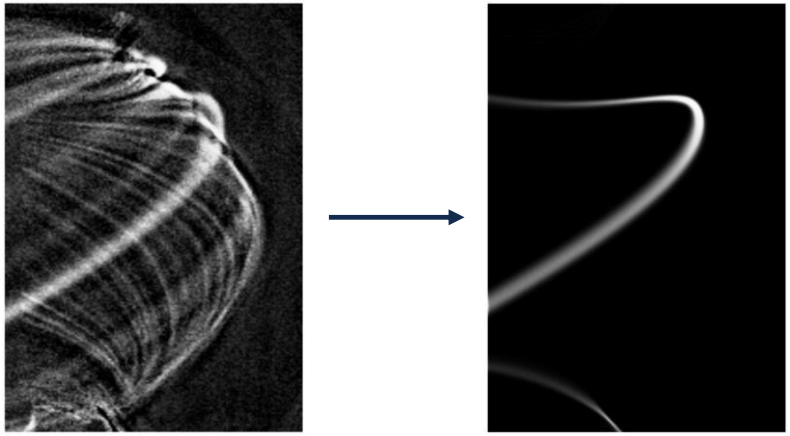
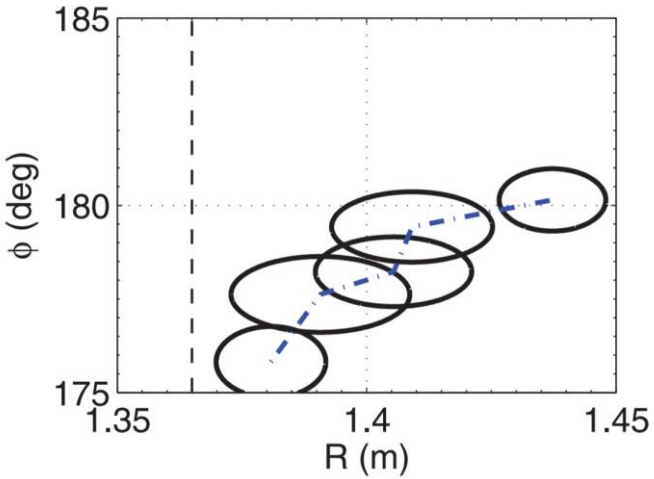
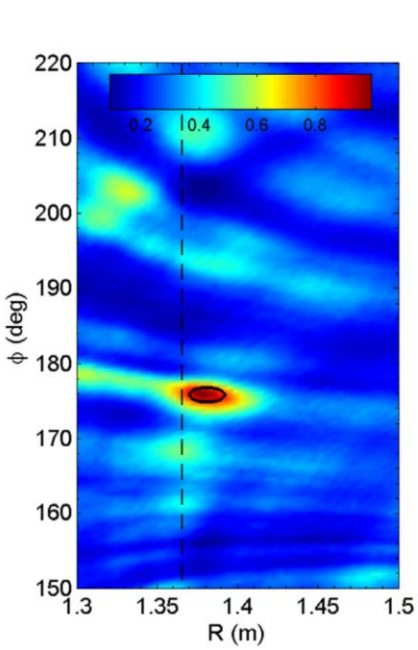
Validation against MAST

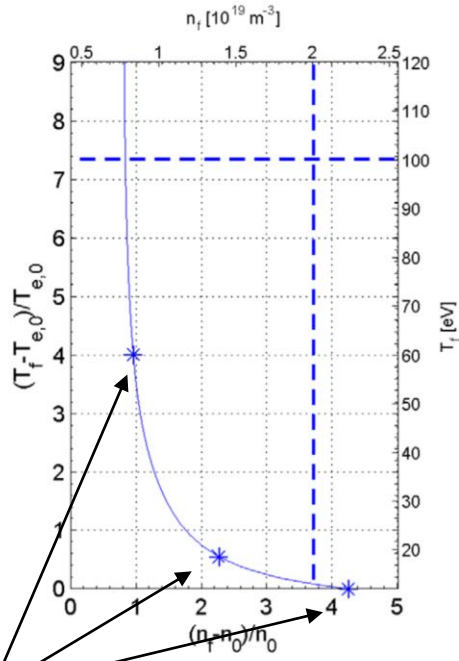


[Militello *et al.*, PPCF (2016)]



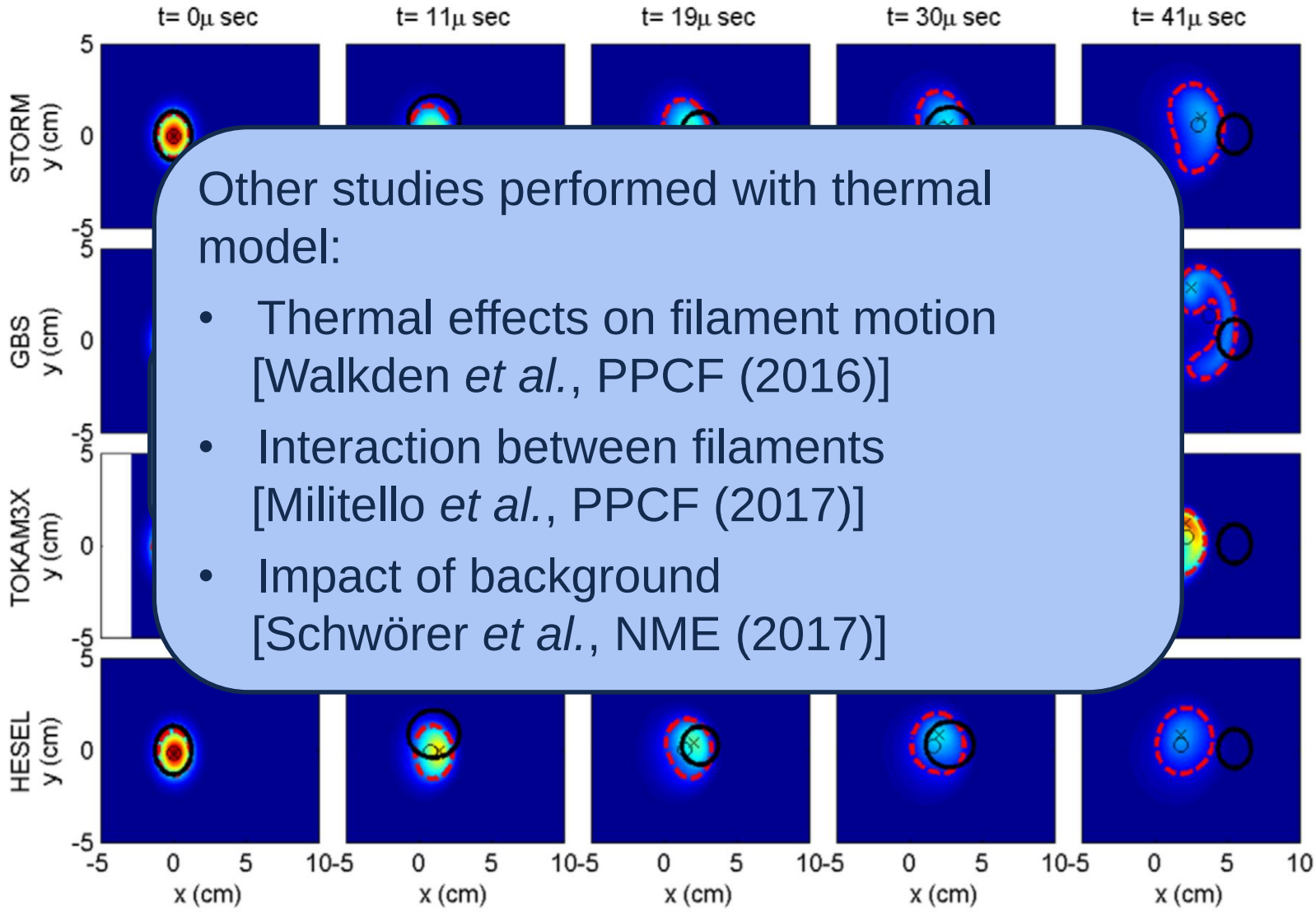
Observable: filament motion





Initial conditions

Validation against MAST



Other studies performed with thermal model:

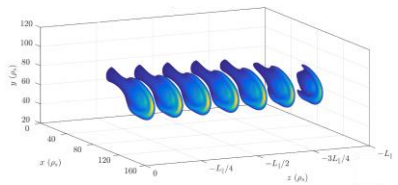
- Thermal effects on filament motion [Walkden *et al.*, PPCF (2016)]
- Interaction between filaments [Militello *et al.*, PPCF (2017)]
- Impact of background [Schwörer *et al.*, NME (2017)]

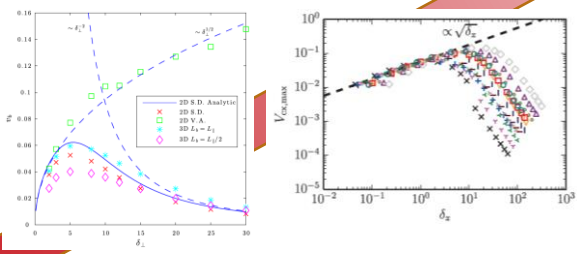
[Militello *et al.*, PPCF (2016)]

STORM: the workhorse of our projects

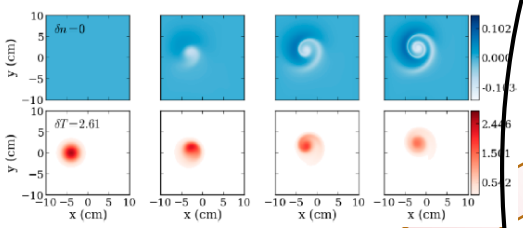
https://github.com/boutproject/STORM

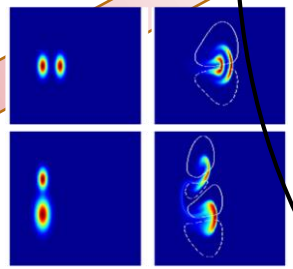
- The STORM isothermal model
- Verification and validation
- Comparison with 2D simulations
- Effects of filaments' amplitude



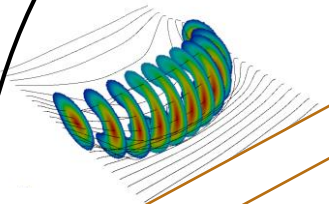


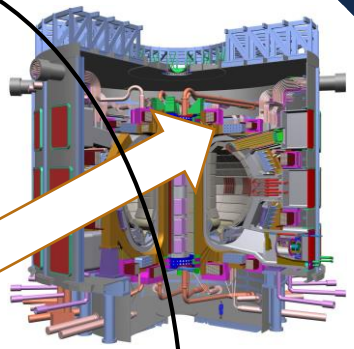
- The STORM thermal model
- Validation

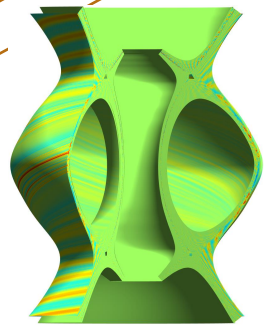




Present







- What's next?
- Plasma turbulence

April 2013

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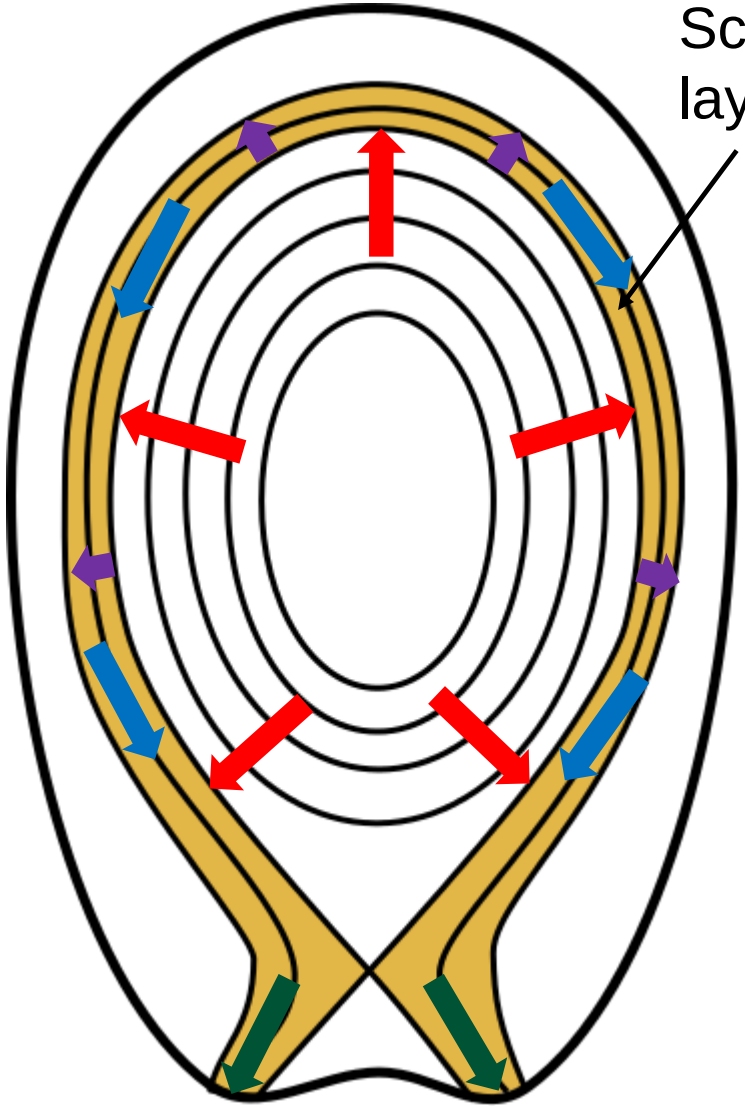
The scrape-off layer (SOL) region



Roles of the SOL

- Heat exhaust

What are the heat and particle loads on vessel components?

How to reduce them?

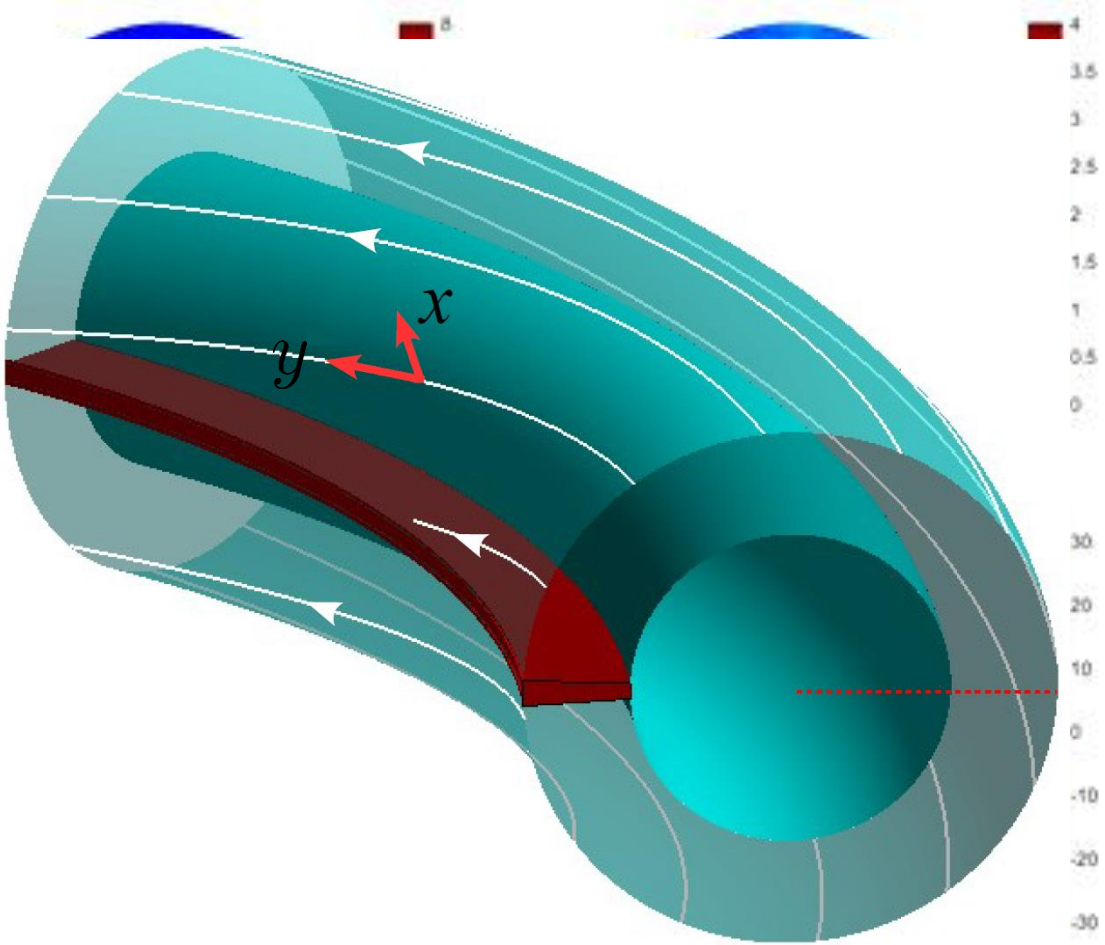
➔Need to understand transport mechanisms in the SOL

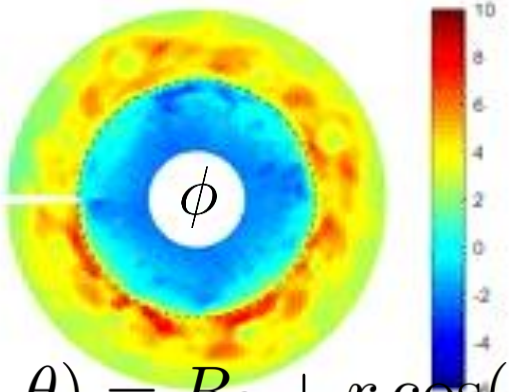
- Filaments (generation, motion,…)
- Turbulence dynamics

Turbulence in s-α geometry

Evolve plasma equilibrium $\Rightarrow$ flux driven $\Rightarrow$ particle and energy sources

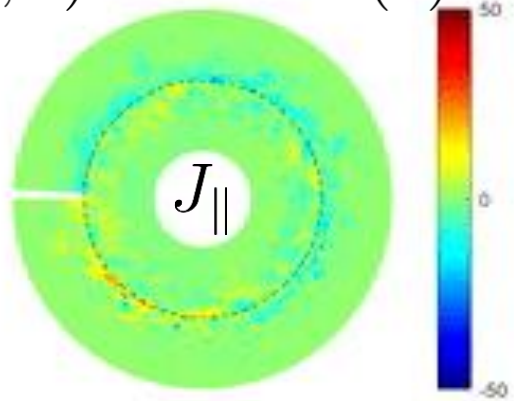
Turbulence typically characterized by $k_r L_{eq} \gtrsim 1 \Rightarrow$ global simulations



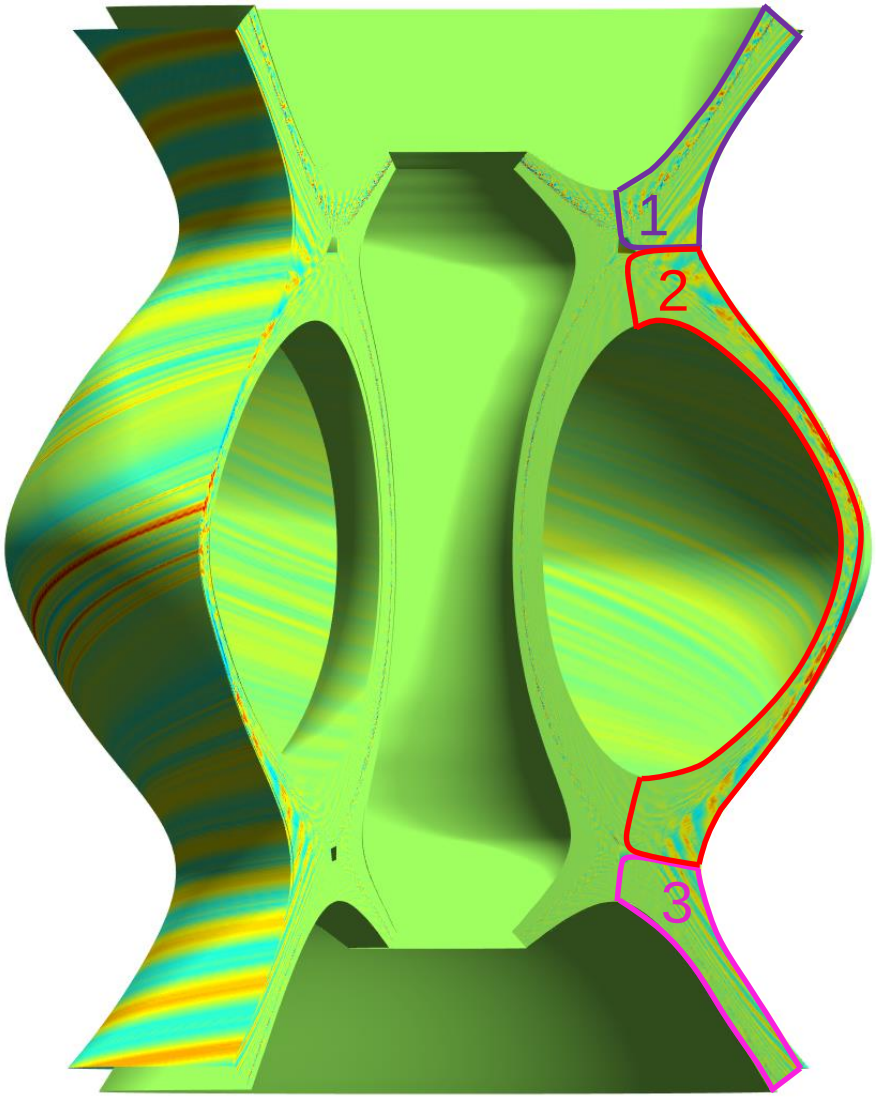


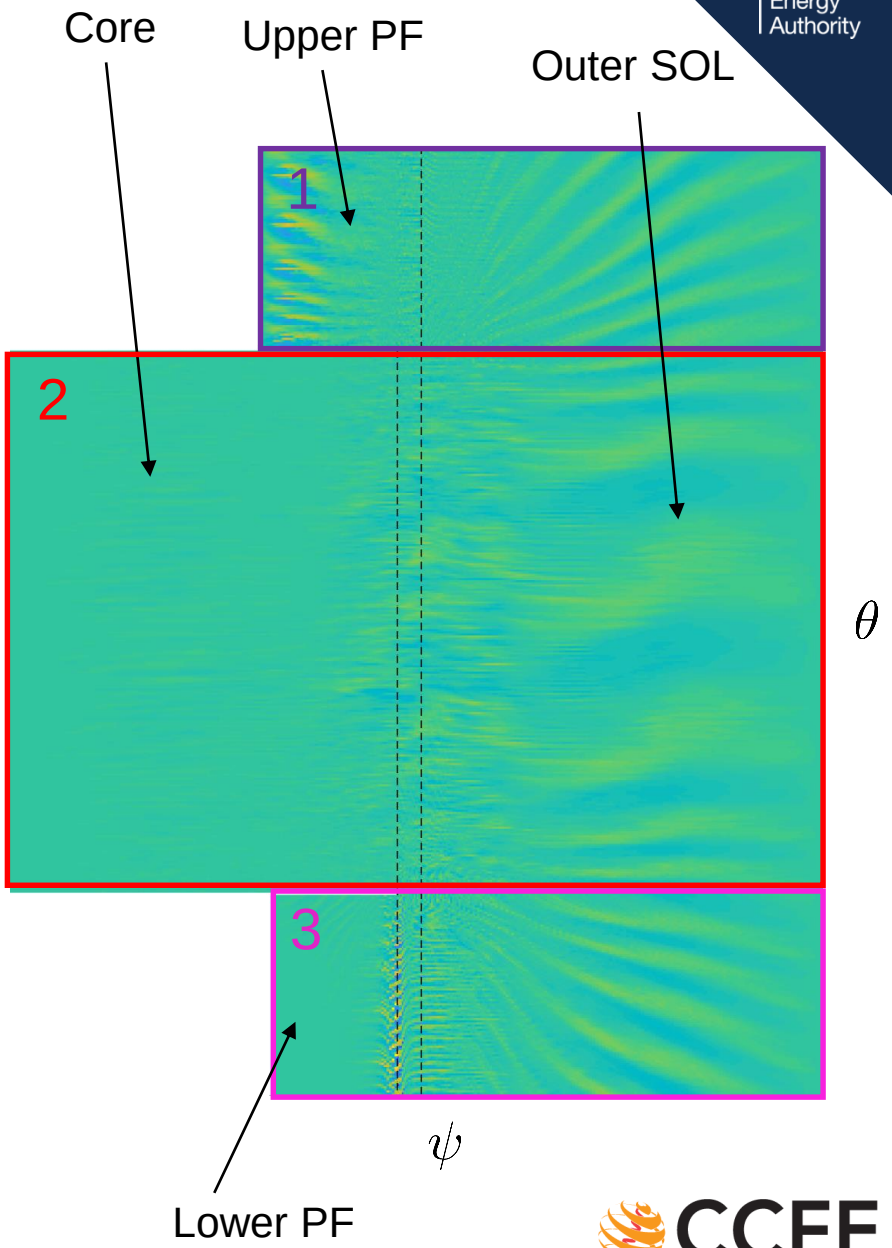
$$R(r,\theta) = R_0 + r\cos(\theta)$$

$$Z(r,\theta) = -r\sin(\theta)$$



MAST simulations





A plasma model for the SOL

UK Atomic Energy Authority

- High collisionality $\nu^* \gg 1$ ⟶ Braginskii equations
- Slow timescales, $\rho_s \ll L_\perp$ ⟶ Drift reduction

$$\mathbf{v}_i = U\mathbf{b} + \mathbf{v}_{E\times B} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d}{dt}\mathbf{v}_{E\times B}$$

- ~~Slab geometry~~
- ~~Isothermal electrons~~
- ~~Boussinesq approximation~~
- Electrostatic ⟶ $\mathbf{E} = -\nabla\phi$

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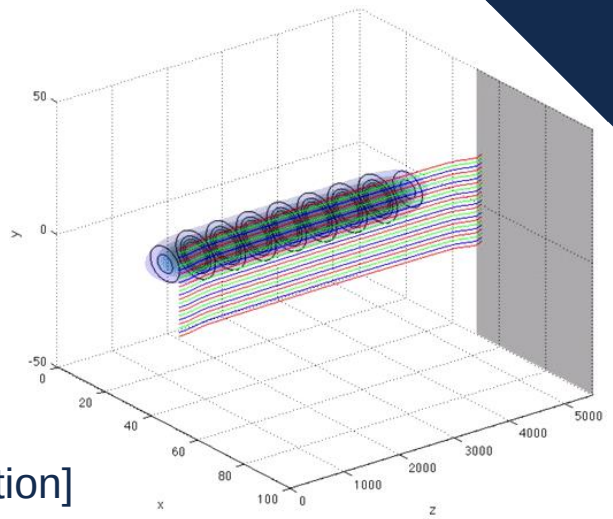
Other activities



- Filaments
  - Electromagnetic effects [Hoare *et al.*, in preparation]
  - Filament separation at the separatrix
  - Magnetic shear effects
  - Neutrals (diffusive model)
- Turbulence
  - Divertor leg [Walkden *et al.*, NME (submitted)]
  - 2D/3D comparison
  - Validation against MAST

A plasma model for the SOL

UK Atomic Energy Authority

- High collisionality $\nu^* \gg 1 \longrightarrow$ Braginskii equations
- Slow timescales, $\rho_s \ll L_\perp \longrightarrow$ Drift reduction

$$\mathbf{v}_i = U\mathbf{b} + \mathbf{v}_{E\times B} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d}{dt}\mathbf{v}_{E\times B}$$

- ~~Slab geometry~~
- ~~Isothermal electrons~~
- ~~Boussinesq approximation~~
- ~~Electrostatic~~

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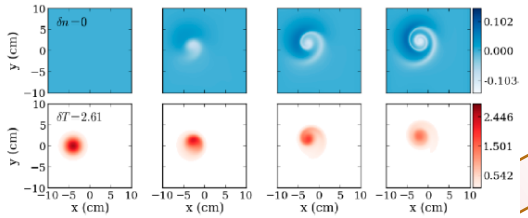
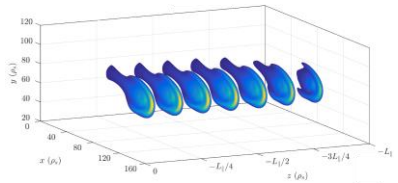
STORM: the workhorse of our projects

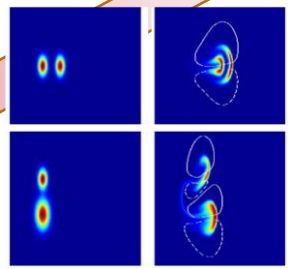
https://github.com/boutproject/STORM

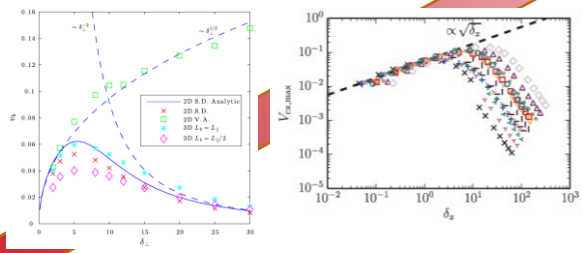
- The STORM isothermal model
- Verification and validation
- Comparison with 2D simulations
- Effects of filaments' amplitude

- The STORM thermal model
- Validation

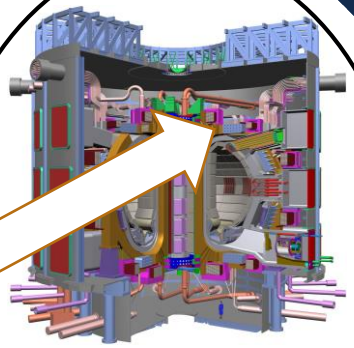




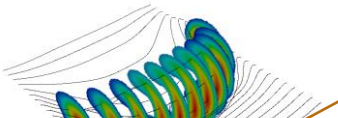


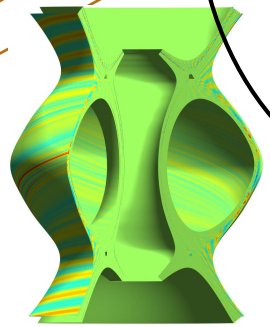


Future



- What's next?





- Plasma turbulence

April 2013

Top priorities for future development

Include

- thermal ions
- kinetic neutrals
- alternative magnetic configurations
- nonlocal effects

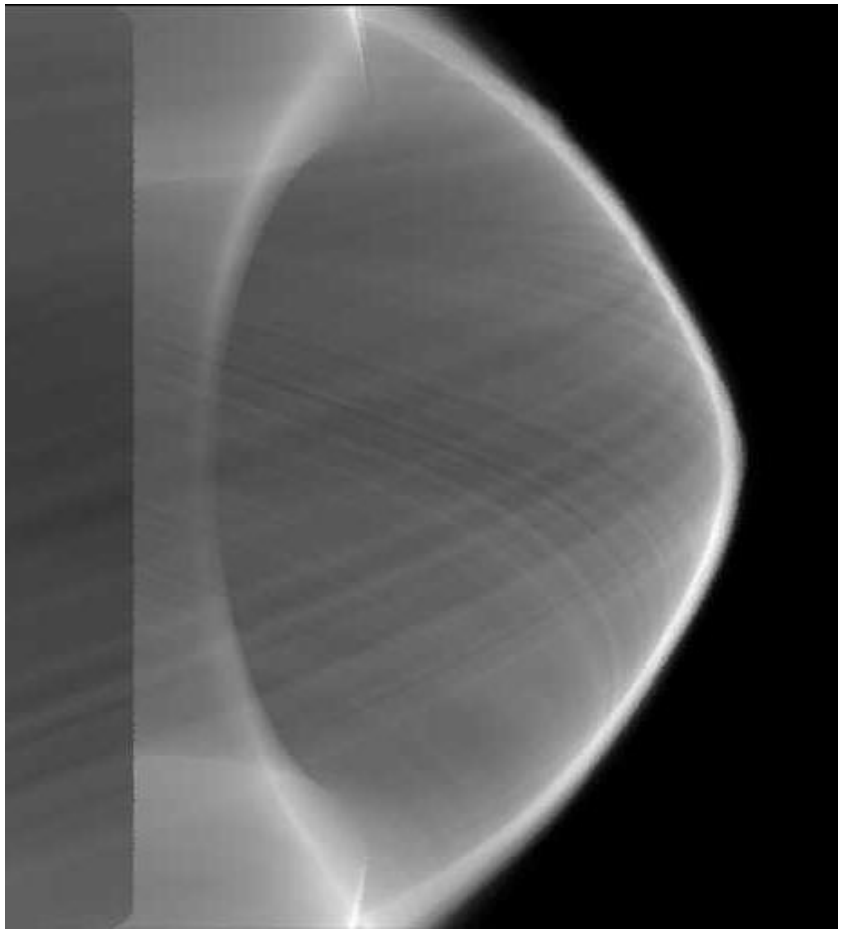
to understand

- first wall erosion
- heat flux at the target.

Numerical necessities:

- Compatibility between shifted grids and shifted metric
- 3D multigrid solver (PETSc)

Image created with CHERAB by Dr. M. Carr



STORM in journal articles

https://github.com/boutproject/STORM

[Easy *et al.*, “Three dimensional simulations of plasma filaments in the scrape off layer: A comparison with models of reduced dimensionality”, PoP (2014)]

[Omotani *et al.*, “The effects of shape and amplitude on the velocity of scrape-off layer filaments”, PPCF (2015)]

[Riva *et al.*, “Blob dynamics in the TORPEX experiment: a multi-code validation”, PPCF (2016)]

[Easy *et al.*, “Investigation of the effect of resistivity on scrape off layer filaments using three-dimensional simulations”, PoP (2016)]

[Walkden *et al.*, “Dynamics of 3D isolated thermal filaments”, PPCF (2016)]

[Militello *et al.*, “Multi-code analysis of scrape-off layer filament dynamics in MAST”, PPCF (2016)]

[Militello *et al.*, “On the interaction of scrape off layer filaments”, PPCF (2017)]

[Schwörer *et al.*, “Influence of plasma background including neutrals on scrape-off layer filaments using 3D simulations”, NME (2017)]

A plasma model for the SOL

- High collisionality $\nu^* \gg 1$ ⟶ Braginskii equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{v}_\alpha) = 0, \ ...$$

- Slow timescales, $\rho_s \ll L_\perp$ ⟶ Drift reduction

$$\mathbf{v}_i = U\mathbf{b} + \mathbf{v}_{E\times B} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d}{dt}\mathbf{v}_{E\times B} \qquad \mathbf{v}_e = V\mathbf{b} + \mathbf{v}_{E\times B} + \mathbf{v}_{de}$$

- Slab geometry ⟶ Magnetic curvature and gradients added artificially

$$\left(\nabla \times \frac{\mathbf{b}}{B}\right) \cdot \nabla A \approx g \frac{\partial A}{\partial z} \qquad g = 2\frac{\rho_{s0}}{R}$$

- Isothermal electrons ⟶ $T = 1$

- Boussinesq approximation ⟶ $\nabla \cdot \left(n \frac{d \nabla_\perp \phi}{dt} \right) \approx n \frac{d \nabla_\perp^2 \phi}{dt}$

- Electrostatic ⟶ $\mathbf{E} = -\nabla \phi$

A plasma model for the SOL

- Continuity equation

$$\frac{\partial n}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla n - \nabla_{\parallel}(nV) + g\left(\overbrace{\frac{\partial n}{\partial z}}^{\nabla\cdot(n\mathbf{v}_{de})} - \overbrace{n\frac{\partial \phi}{\partial z}}^{n\nabla\cdot\mathbf{v}_{E\times B}}\right) + \nabla\cdot(\mu_n\nabla n) + S_n$$

- $\nabla\cdot\mathbf{J} = 0$

$$\frac{\partial \Omega}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla\Omega - U\partial_{\parallel}\Omega + \frac{1}{n}\overbrace{\nabla_{\parallel}\left[n(U-V)\right]}^{\nabla\cdot\mathbf{J}_{\parallel}} + \overbrace{\frac{g}{n}\frac{\partial n}{\partial z}}^{\nabla\cdot\mathbf{J}_D} + \nabla\cdot(\mu_\Omega\nabla\Omega)$$

- Ohm's law

$$\frac{\partial V}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla V - V\partial_{\parallel}V + \frac{m_i}{m_e}\left[\partial_{\parallel}\phi + \nu_{\parallel}(U-V) - \frac{1}{n}\partial_{\parallel}n\right] - V\frac{S_n}{n}$$

- Parallel ion momentum equation

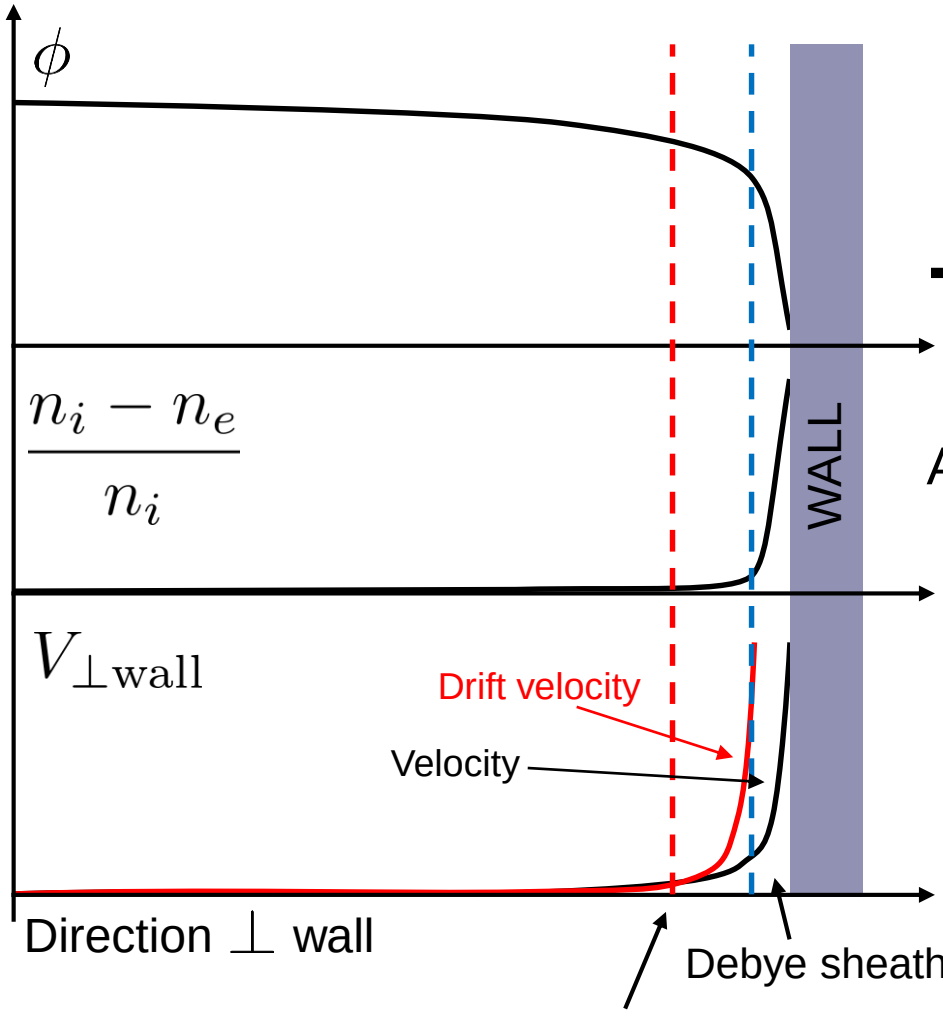
$$\frac{\partial U}{\partial t} = -\mathbf{v}_{E\times B}\cdot\nabla U - U\partial_{\parallel}U - \partial_{\parallel}\phi - \nu_{\parallel}(U-V) - U\frac{S_n}{n}$$

- Poisson's equation

$$\Omega = \nabla_{\perp}^2\phi$$

A plasma model for the SOL

Drift approximation breaks at magnetic pre-sheath entrance



➔ Boundary conditions to be applied at magnetic pre-sheath entrance

Assuming $B \perp$ wall

$$U \gtrless \pm 1$$

$$V = \pm \exp(\phi_{\text{wall}} - \phi)$$

Verification of the parallel dynamics

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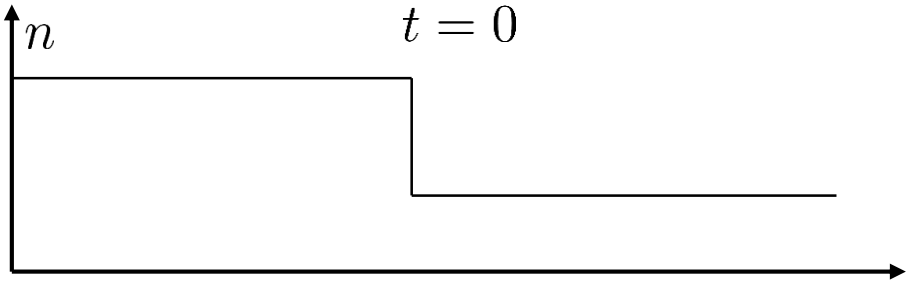
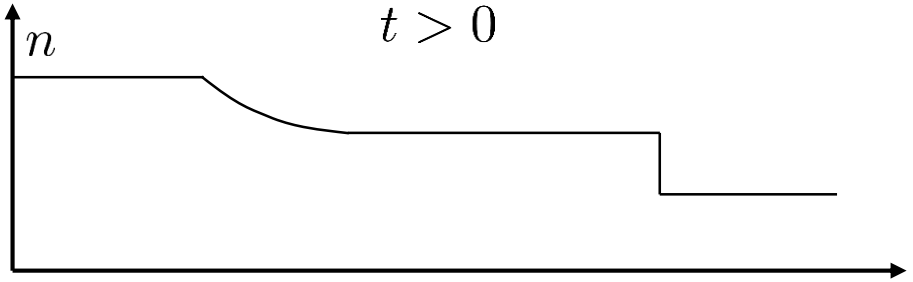
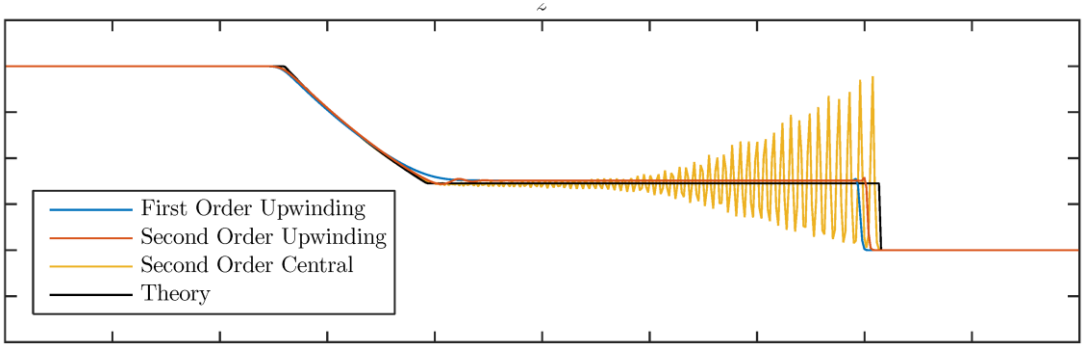
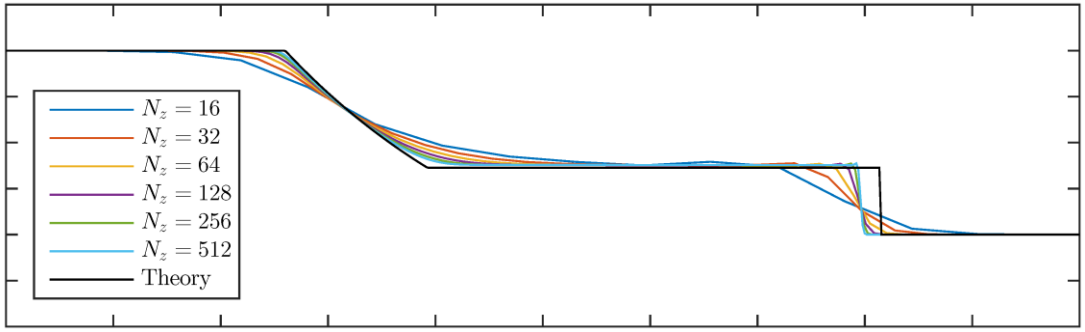
The shock tube problem









[Easy, Ph.D. Thesis (2016)]

- Central scheme introduces strong oscillations
- Overall good agreement for high resolution

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Code verification, order-of-accuracy test

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Our model: $M(f) = 0$, f unknown

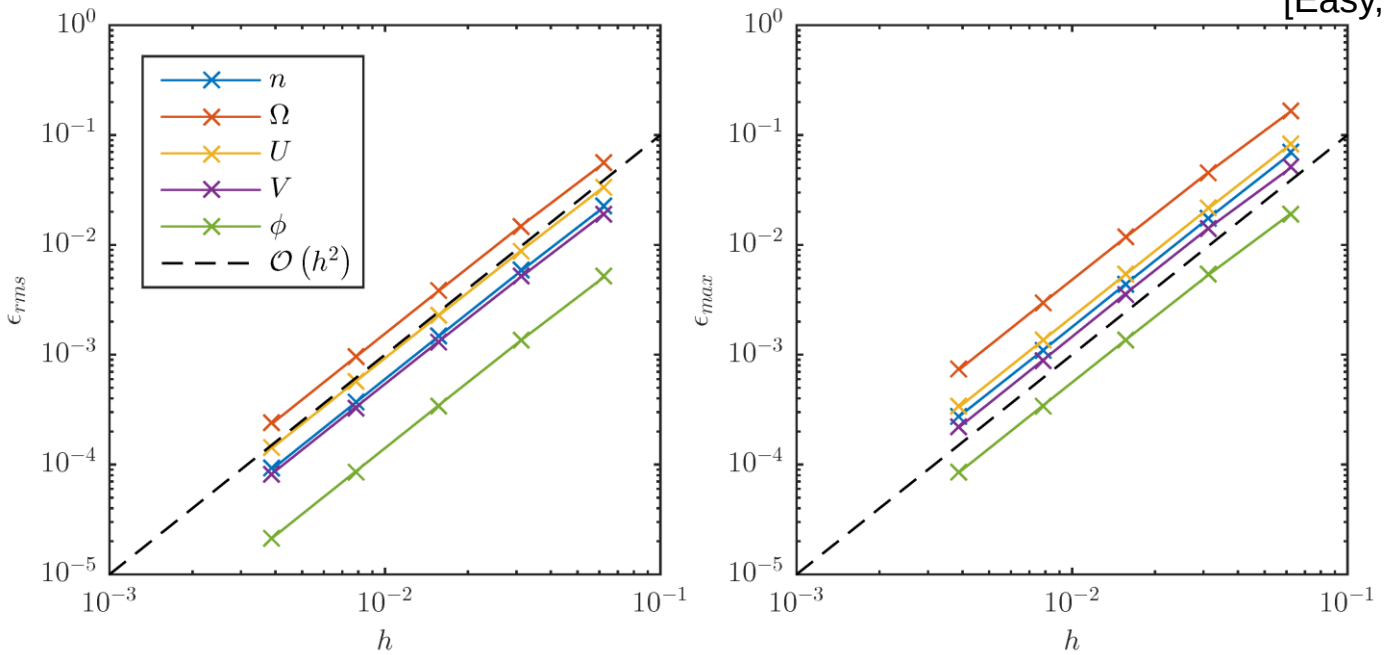
Solve $M_h(f_h) = 0$ for f_h, but $\epsilon_h = \|f - f_h\| = ?$

Is $\epsilon_h = \|f - f_h\| = h^p + \mathcal{O}(h^{p+1})$?

Method of manufactured solutions [Roache *et al.*, AIAA J. (1984), Riva *et al.*, PoP (2014)]

1) Choose arbitrary function g, compute $S = M(g)$
2) Solve $M_h(g_h) - S = 0 \Rightarrow \epsilon_h = \|g - g_h\|$

[Easy, Ph.D. Thesis (2016)]



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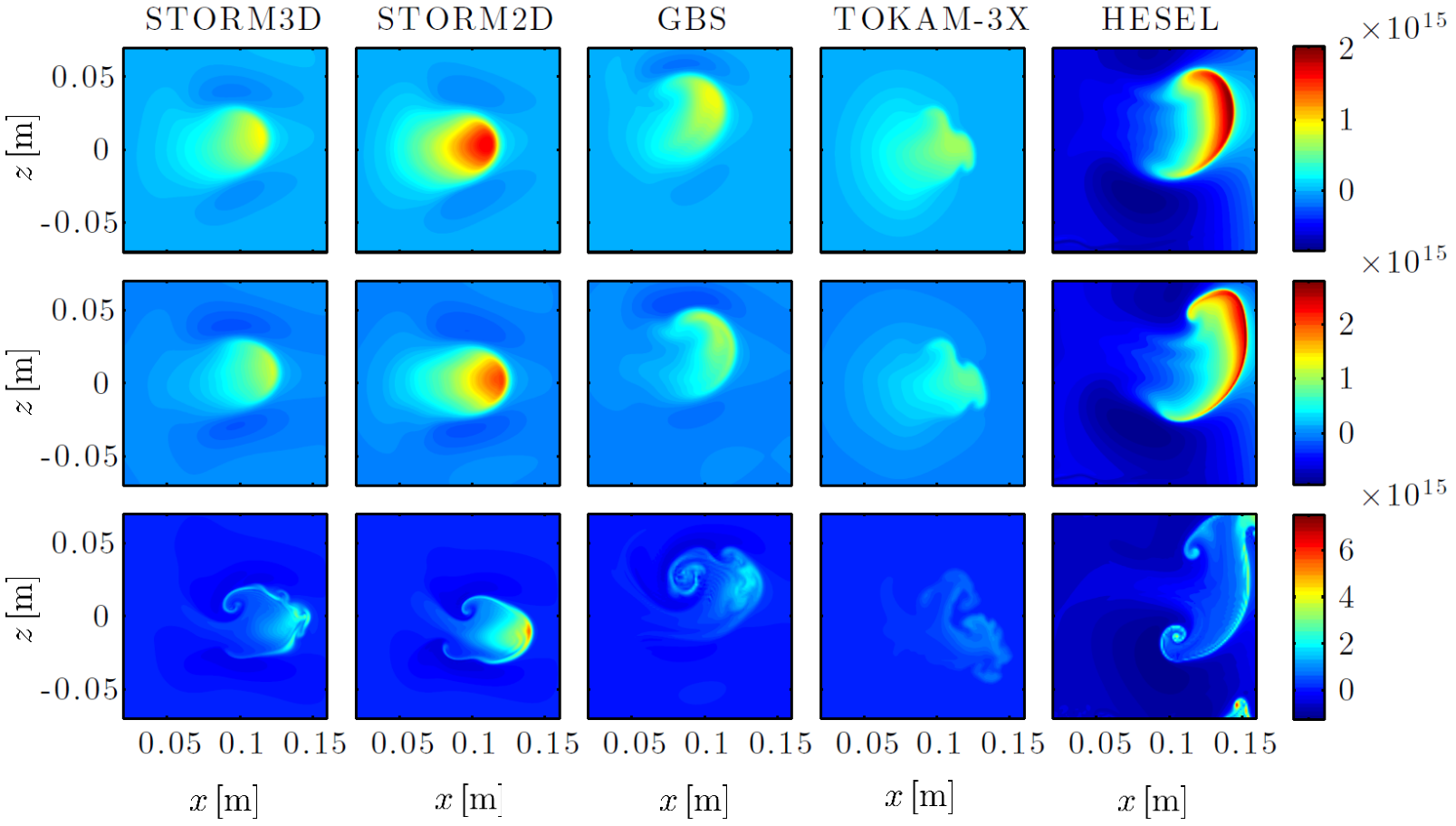
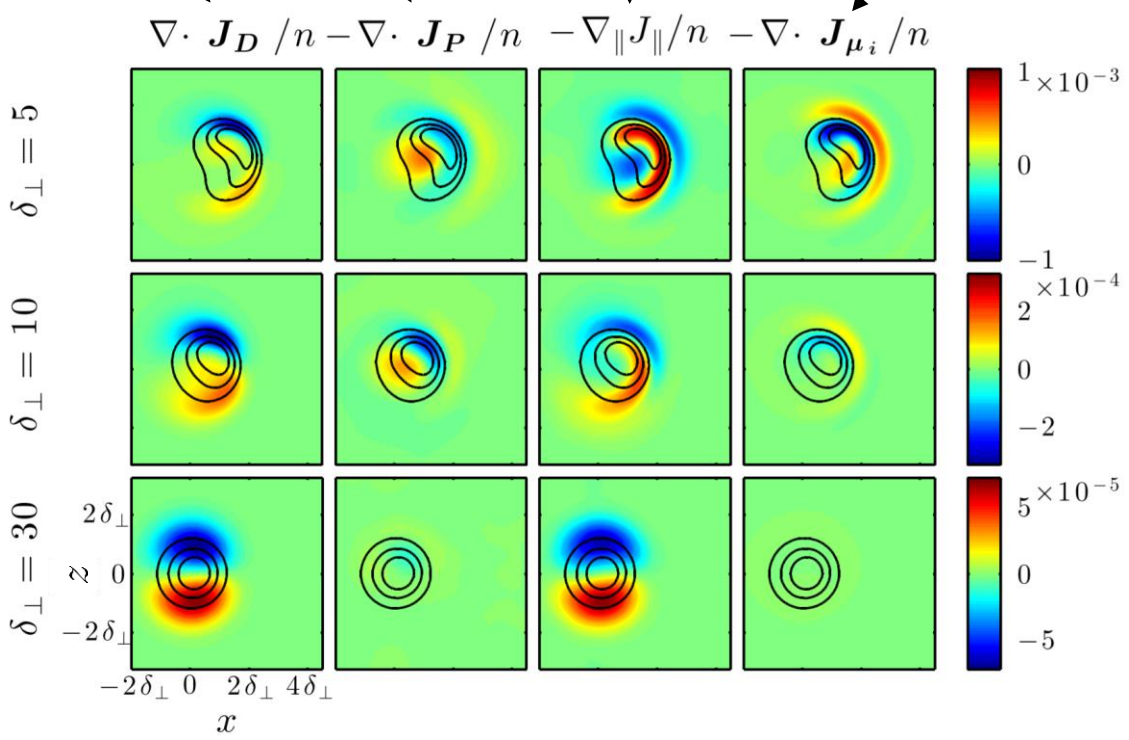
Validation against TORPEX experiment



[Riva *et al.*, PPCF (2016)]

Effects of filaments' perpendicular size

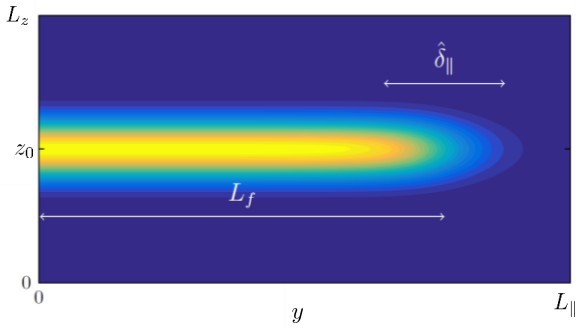
$$-\frac{g}{n}\frac{\partial n}{\partial z} = -\frac{d\Omega}{dt} + \frac{1}{n}\nabla_{\parallel}\left[n(U-V)\right] + \nabla\cdot(\mu_{\Omega}\nabla\Omega)$$

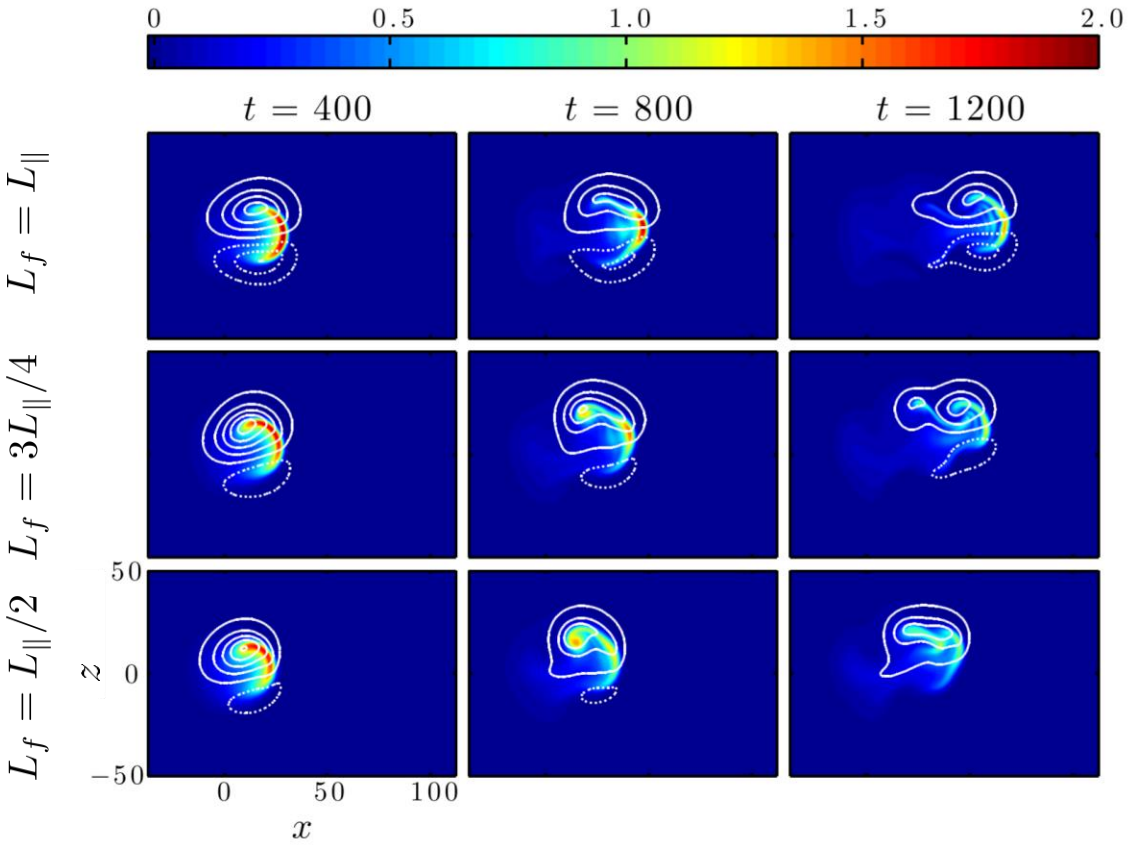


- Diamagnetic and polarization currents negligible for large filaments
- More complex current path for small filaments

[Easy *et al.*, PoP (2014)]

Effects of filaments' parallel extent

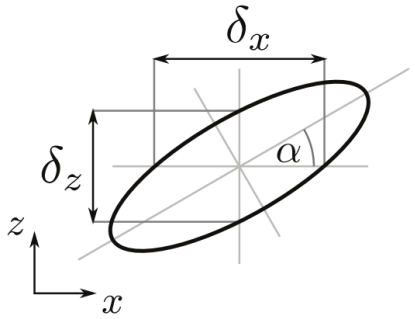




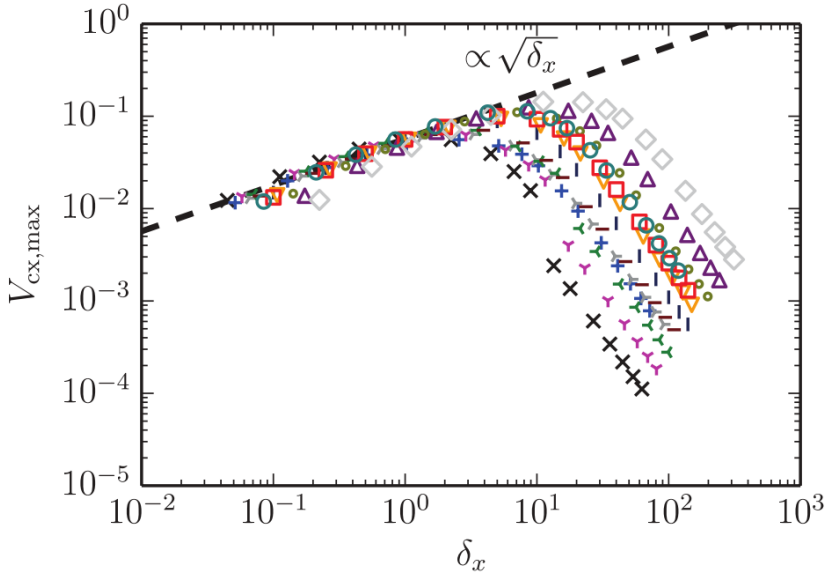
- Connected filaments display faster radial propagation
- Filaments spin if not connected with the sheath

[Easy *et al.*, PoP (2014)]

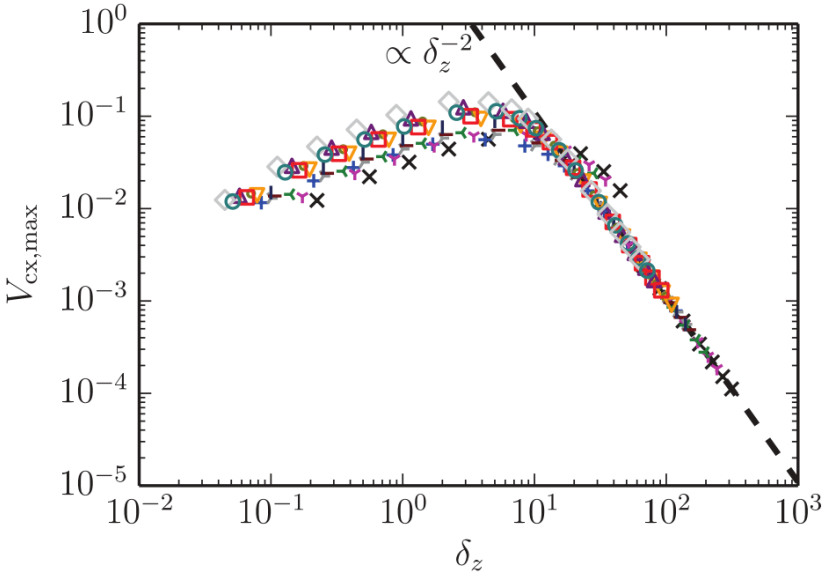
Effects of filaments' shape

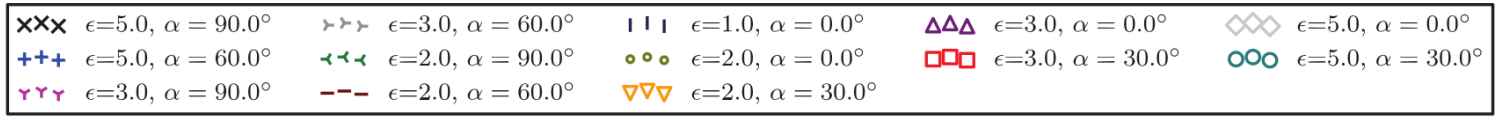


Inertial regime $\propto \sqrt{\delta_x}$



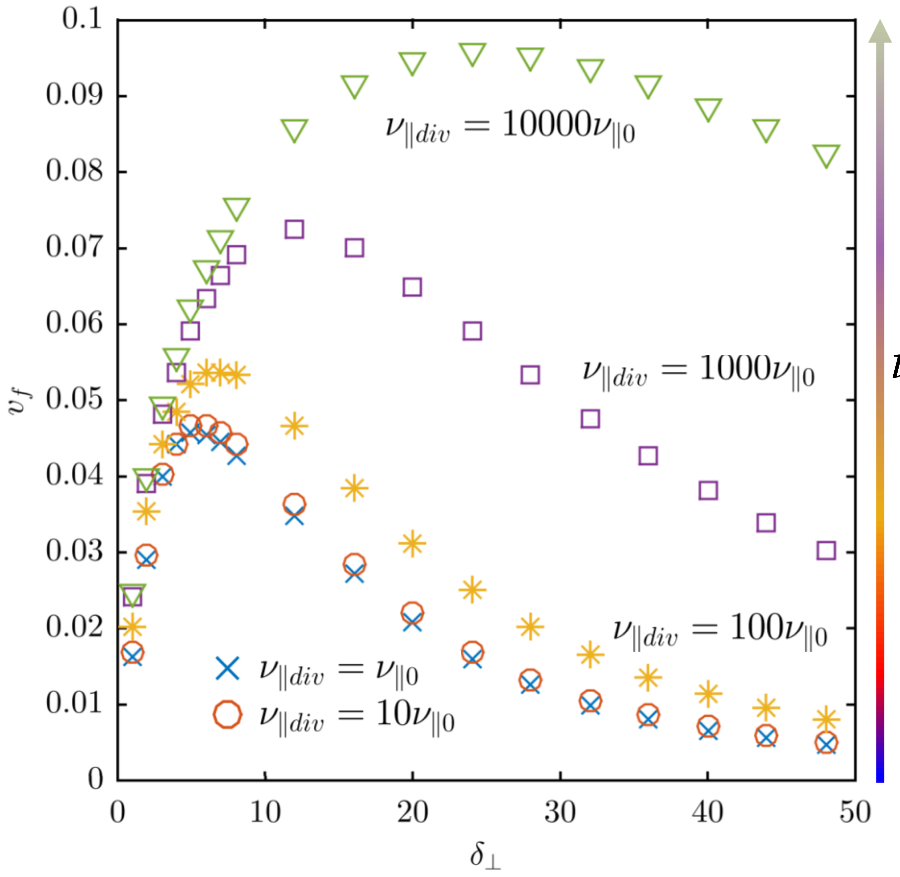
Sheath current regime $\propto \delta_z^{-2}$

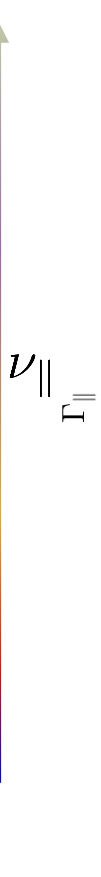


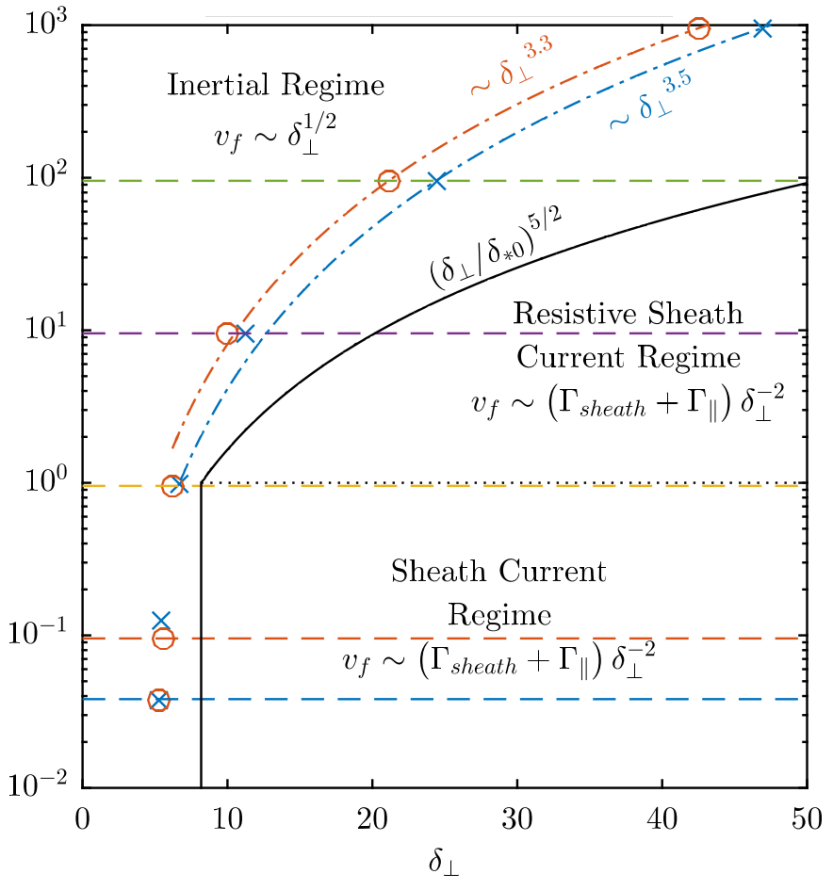


[Omotani *et al.*, PPCF (2015)]

Effects of plasma resistivity





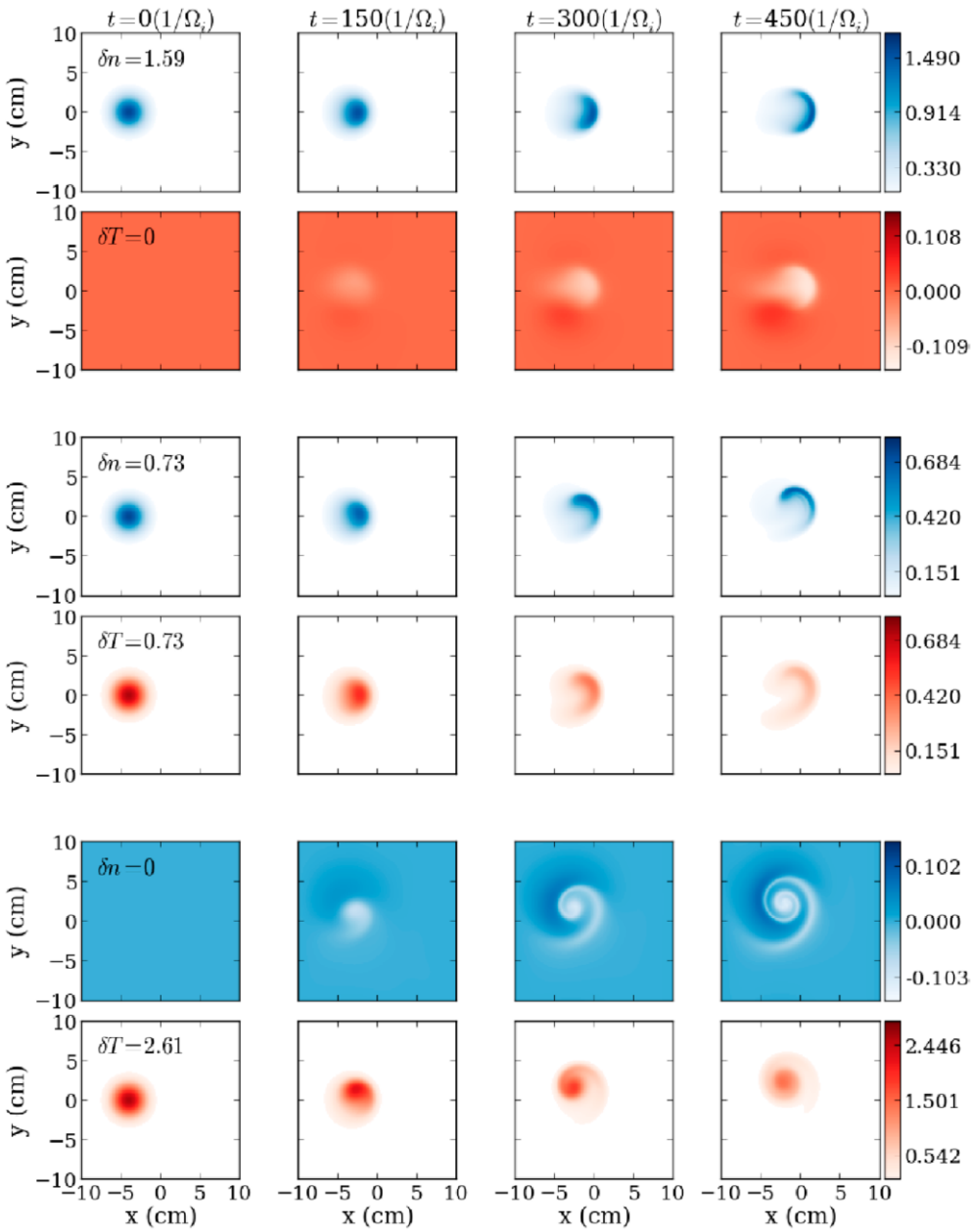


$\nu_\parallel$ disconnects filaments from the target, shifting the transition between sheath current and inertial regime

Two-region model
[Myra *et al.*, PoP (2006)]

[Easy *et al.*, PoP (2016)]

Thermal effects

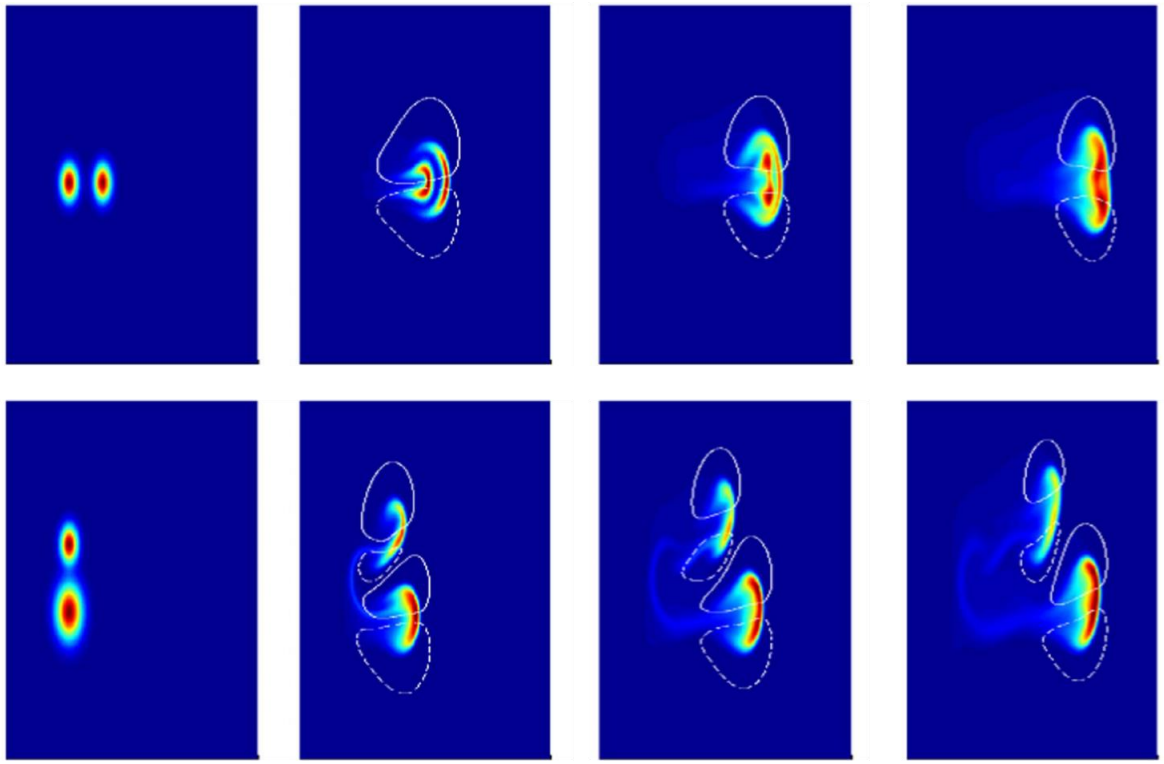


If $\frac{\delta T}{T_{bg}} \gg \frac{\delta n}{n_{bg}}$:

- Increased propagation in binormal direction
- Reduced propagation in radial direction
- Faster parallel pressure losses

[Walkden *et al.*, PPCF (2016)]

Filament interaction

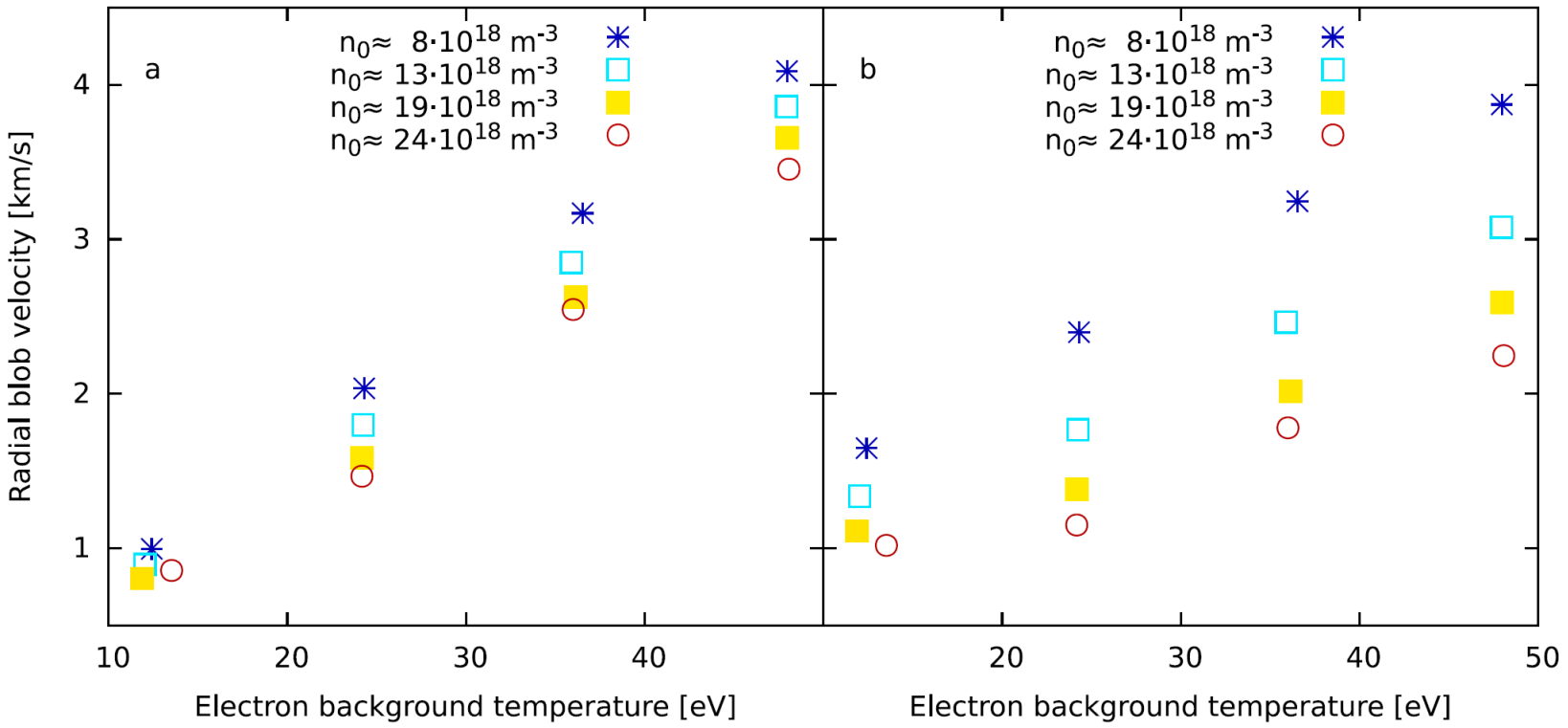


Filaments separated by more than 5 widths

$\Rightarrow$ like independent filaments

[Militello *et al.*, PPCF (2017)]

Effects of plasma background



- Radial velocity decreases by increasing n_0
- Radial velocity increases by increasing T_0

[Schwörer *et al.*, NME (2017)]

Electromagnetic effects

Do filaments affect field lines?

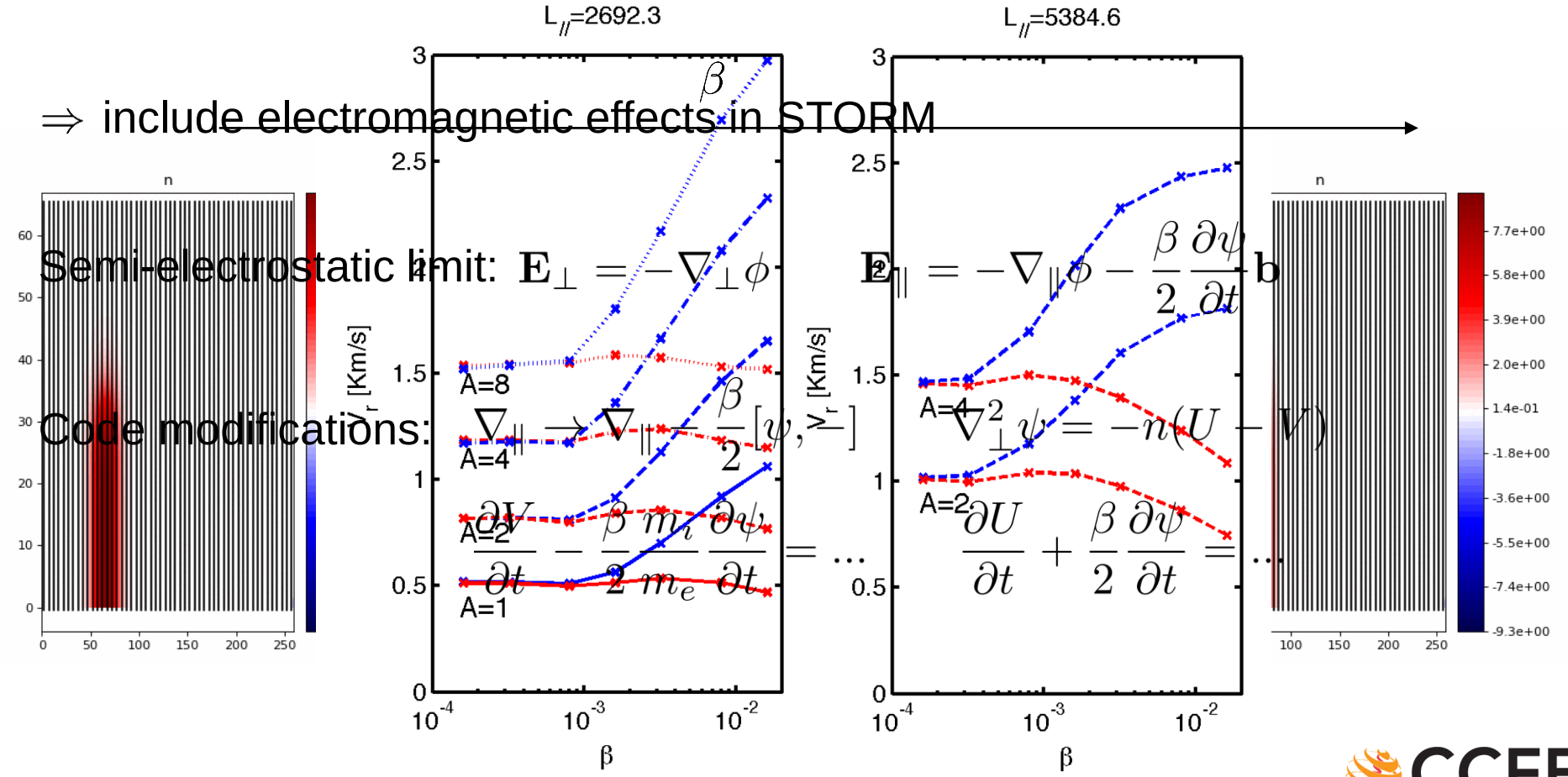
Do filaments behave differently when including electromagnetic effects?

$\Rightarrow$ include electromagnetic effects in STORM

Semi-electrostatic limit: $\mathbf{E}_\perp = -\nabla_\perp \phi \qquad \mathbf{E}_\parallel = -\nabla_\parallel \phi - \frac{\beta}{2}\frac{\partial \psi}{\partial t}\mathbf{b}$

Code modifications: $\nabla_\parallel \rightarrow \nabla_\parallel - \frac{\beta}{2}[\psi, \ldots] \qquad \nabla_\perp^2 \psi = -n(U - V)$

$\frac{\partial V}{\partial t} - \frac{\beta}{2}\frac{m_i}{m_e}\frac{\partial \psi}{\partial t} = \ldots \qquad \frac{\partial U}{\partial t} + \frac{\beta}{2}\frac{\partial \psi}{\partial t} = \ldots$

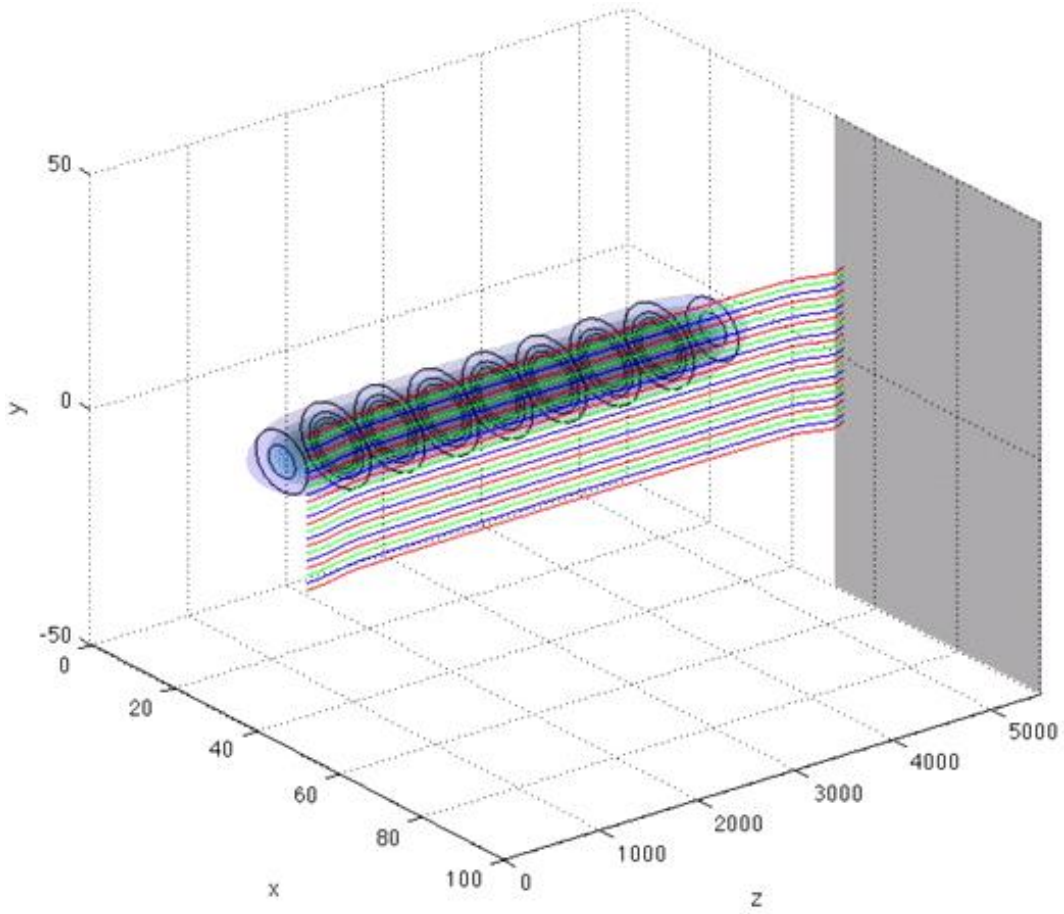


[Hoare *et al.*, PPCF (submitted)]

Filament separation

UK Atomic Energy Authority

Understand how filaments cross the separatrix



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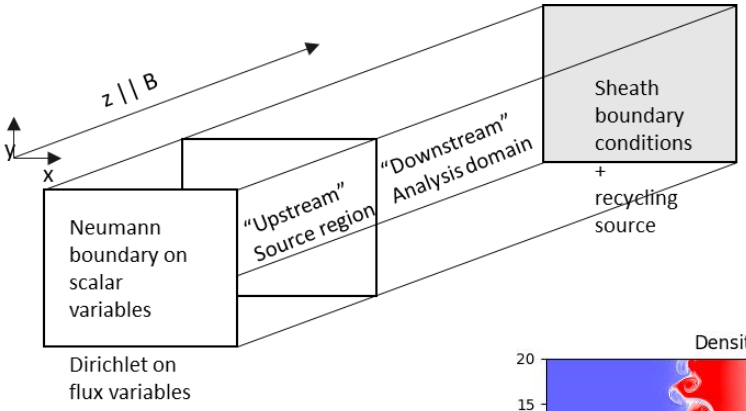
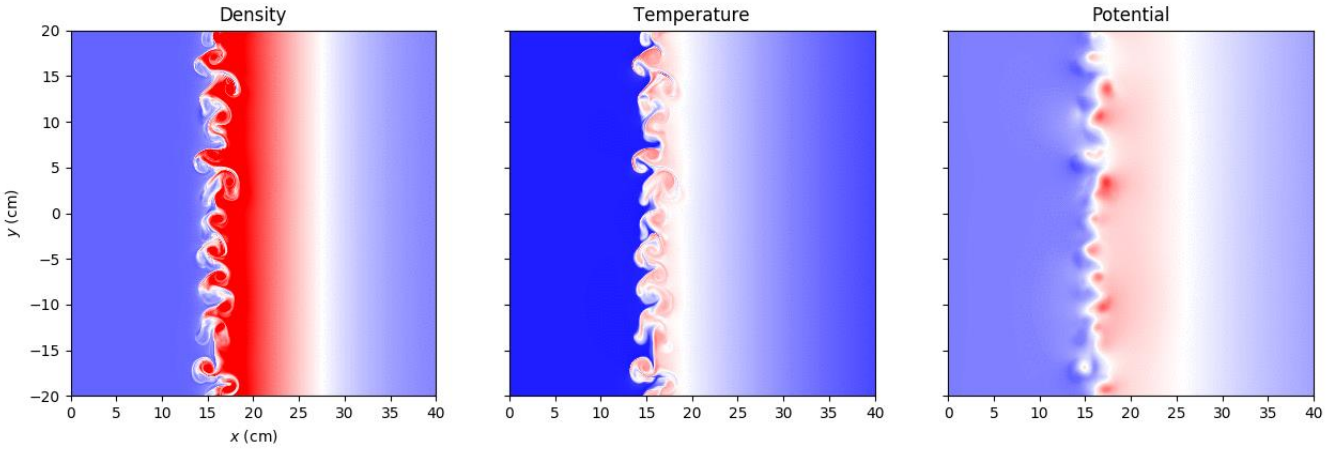
Turbulent mixing in divertor legs

UK Atomic Energy Authority

Understand how turbulence spreads heat and particles in the divertor leg





[Walkden *et al.*, PSI (2018)]

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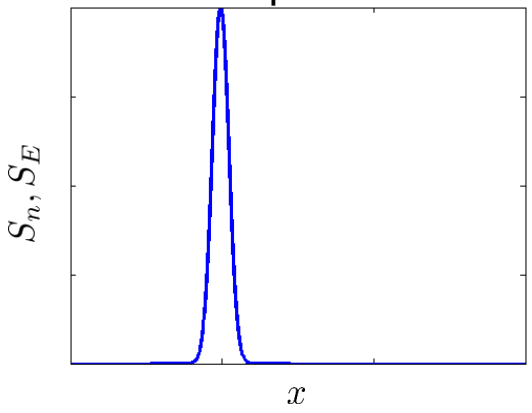
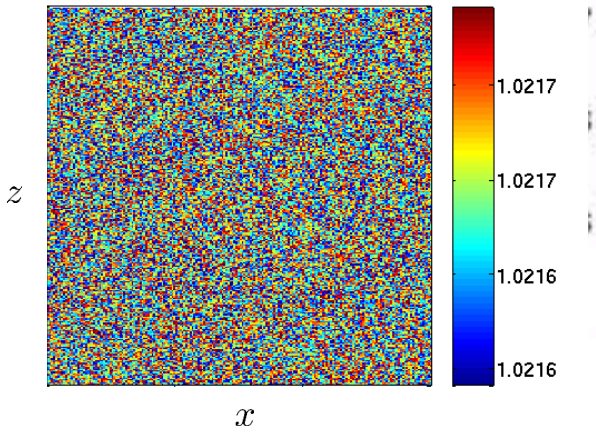
Simulating plasma turbulence

UK Atomic Energy Authority

Source of particles and heat

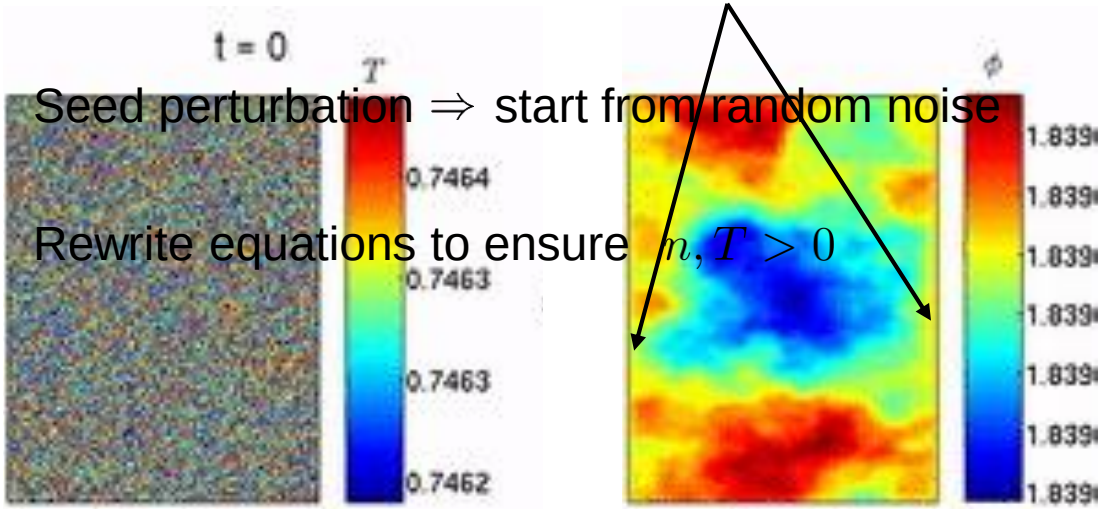


Initial random noise



- Evolve plasma equilibrium from arbitrary conditions
- Seed perturbation $\Rightarrow$ start from random noise
- Rewrite equations to ensure $n, T > 0$

Explored different boundary conditions



$$\frac{\partial n}{\partial t} = f_n(t, n, T, ...) \rightarrow \frac{\partial \log(n)}{\partial t} = \frac{f_n(t, n, T, ...)}{n}, \quad \frac{\partial T}{\partial t} = f_T(n, t) \rightarrow \frac{\partial \log(T)}{\partial t} = \frac{f_T(t, n, T, ...)}{T}$$

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